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Literature Review and Background Research

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WATER SUPPLY SIMULATION MODEL

VOLUME II - LITERATURE REVIEW AND BACKGROUND RESEARCH

by

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16. ABSTRACT

This three-volume report describes the development of a water supply simulation model (WSSM), a system of computer programs that allows for a systematic evaluation of the physical and economic characteristics of a water distribution system in a spatial framework.

The WSSM concept views a water utility as a network overlayed upon a spatial distribution of supply and demand. The model explicitly deals with the relationship of delivered water costs to the service requirements of spatially distributed demand. Once an adequate hydraulic simulation has been made, the model can be used to determine costs, travel time, and contaminant concentrations at various points in the network.

The model has been calibrated and tested on several water supply systems including a small utility in New Vienna, Ohio, and the Kenton County Water District No. 1 in Kenton County, Kentucky. Volume 1 of this study describes the development of the model and its underlying principals. Volume 2 discusses some of the engineering and economic concepts used in developing the model. Volume 3 is a users manual for the model.

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FOREWORD

The Environmental Protection Agency was created because of increasing public and governmental concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimonies to the deterioration of our natural environment. The complexity of that environment and interplay among its components require a concentrated and integrated attack on the problem.

Research and development is the first step in problem solution, and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems (1) to prevent, treat, and manage wastewater, solid and hazardous waste, and pollutant discharges from municipal and community sources, (2) to preserve and treat public drinking water supplies, and (3) to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is a product of that research and is a most vital communications link between the research and the user community.

One of the major problems facing the U.S. Enivronmental Protection Agency is meeting the requirements of the Safe Drinking Water Act. The Act emphasizes the need to consider economics in all phases of its implementation. This report presents results from a study on the development of a water supply system simulation model. The model allows the user to evaluate the tradeoffs involved in making decisions concerning system expansion, water production and facility location. It should be useful to water supply managers and planners.

Francis T. Mayo, Director
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ABSTRACT

For the water supply industry, the Safe Drinking Water Act of 1974 (Public Law 93-523) has brought about a fundamental re-examination of the way water is handled before it is delivered to the customer. The U.S. Environmental Protection Agency (EPA), designated as responsible for establishing a program that will carry out the Act's provisions, is required to issue regulations, while state agencies are to develop water supply programs, and local governments to pursue these programs. Also, water utilities are required to monitor drinking water quality.

A primary feature of the Act is that economics must be considered before regulations are promulgated. An analysis of the regulations to be promulgated under the Act indicates that its economic effects will be minor on large water supply systems, but that there may be a potentially serious economic impact on small water supply systems due to the high unit costs generally associated with small treatment plants.

One option that might provide relief from this adverse economic impact is for a small system to join with other small systems or with a larger system to form a regional water supply. Presumably, the economies of scale associated with a regional system would benefit small system consumers. Historically, few tools and techniques have been available to assist water supply operators and planners in the analysis of these and related issues.

The effort described in this report has been specifically directed at the hydraulic and economic behavior of water distribution networks, through the development of data management, display, and simulation modeling capability for a wide variety of issues involving such networks. A flexible approach, which will aid in the analysis of water supply system problems, has been devised and implemented through development of a modular set of transportable computer programs.

This report is Volume II of a three-volume series that presents detailed information concerning development of the WSSM and is an inhouse compliment to the work described in Volumes I and III. This volume deals with the background studies and research leading to development of the WSSM. The WSSM can be used to study some of the economic trade-offs associated with regional water supply systems, as well as many other important issues in water supply. The version of the WSSM described in this report was developed through a contract with W. E. Gates and Associates, Batavia, Ohio and Fairfax, Virginia (Contract No. 68-03-2941) and is an outgrowth of an earlier pilot implementation created by EPA's Drinking Water Research Division and the University of Cincinnati Computer Center.

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The current version of the WSSM, as presented in this report, was developed by W. E. Gates and Associates, Batavia, Ohio, under Contract No. 68-03-2041. Dr. Richard Males served as principal investigator, Mr. Paul Wehrman performed much of the systems analysis and programming, and Dr. William Gates served as senior project advisor. Dr. Robert M. Clark served as project officer for USEPA. The authors would like to acknowledge the assistance of Ms Patricia Pierson in preparing this manuscript.

INTRODUCTION

As described in Volume I of this three volume set, EPA's Water Supply Research Division initiated a program to develop techniques and methodologies to allow for the evaluation of regional economic impacts for water supply. The model will assist in providing insights into other water related economic issues such as spatial pricing and costing, conservation policies, user class subsidization, and fire protection capacity.

The model, called the Water Supply Simulation Model (WSSM), is the result of a joint effort by the U.S. Environmental Protection Agency and W. E. Gates and Associates. It incorporates a series of submodels to describe the various aspects of the economic, demographic, and hydraulic systems that make up a water utility.

Development of the model was based on a number of studies dealing with cost of service pricing and spatial variations in water supply cost. One of the first efforts conducted by the Drinking Water Research Division that dealt with the issue of cost variations in a water utility service area was a study conducted by the University of Cincinnati. The purpose of the research was as follows:

1. Develop a methodology for analyzing the cost of delivering finished water to water utility customers. The Cincinnati Water Works was used as a reference system. Costs were analyzed principally in terms of the major user classes (residential, industrial and commerical). Distance and altitude were analyzed explicitly as factors which determine costs.
2. Evidence was acquired on the nature and extent of cost-rate differentials or subsidies, among the customer classes listed above.

Two limitations of the study results were as follows:

1. An inability to precisely detail the impact of distance on the cost of water supply.
2. A lack of ability to explicitly measure the impacts of the provision of water for fire protection on measured costs.

This study was crucial to development of the WSSM and information from this study as well as other relevant studies that are related to the development of the Water Supply Simulation Model will be discussed in this volume. The first section presents a literature review of the cost of water supply.

LITERATURE REVIEW ON THE COST OF WATER SUPPLY

The costs of providing a safe and potable water supply for a regional and metropolitan area is becoming an increasingly important factor for water supply utilities. Expansion of the capacity to satisfy demand, as occurred in the 1940's, 1950's, and 1960's, may not be warranted due to excessive investment cost. In the 1970's and 1980's, future expansion must be carefully analyzed in terms of efficiency of resource use and the effect on total water supply costs, as well as adequacy of supply.

Increased costs are a major problem in the water supply industry. In 1965, capital requirements exceeded two billion dollars and were estimated to be about three billion in 1975.[1] Operating costs continue to increase as inflation persists. Comprehensive analyses of costs are necessary to improve decision making. Without such research, decisions on capital expansion and replacement, level and structure of utility rates, and general operating procedure will be hampered. Adequate supply to meet water demand is an important factor, but knowledge of the costs to meet that demand are crucial.

PRINCIPAL COST COMPONENTS

In general, a water supply system's costs can be broken down into five major categories: acquisition, treatment, transmission, distribution, and support services.[2] A brief synopsis of each follows.

The cost of acquisition involves the collection of raw water from a surface water source (lake or stream) or ground water source (well or spring). Pumping and plant facility cost, labor, and energy are the major portions of acquisition cost.

Treatment to produce a safe and palatable water supply can be very complicated or straight-forward, depending upon the input quality of the raw water and the output quality desired. Treatment generally comprises the following steps: settling, mixing of chemicals, flocculation, and filtration. Use of other processes for softening or removing iron or manganese are dependent on local management decisions. The costs of treatment include labor, chemicals, sand, power, and depreciation on the physical plant.

Transmission pipe lines are the major trunk lines used to transport large volumes of water. They connect the treatment plant to the pumping station, if gravity tunnels are not used, and the distribution system. Pumping stations, pipe lines, and energy comprise the major costs of transmission.

Distribution works include the meters, pipe lines, and storage facilities (water tanks) necessary to convey water from the transmission system to the customer. A pumping station might also be involved if ground-storage exists. Therefore, distribution systems include the cost of pipe lines, water towers, pumping stations, and energy.

The final cost category is support serivces. Administration, interest on the debt, meter reading, billing, revenue collection, and the equipment involved are the major elements in this category. This is a highly labor intensive operation even though computers may be employed to speed work flow. The above five components represent a general categorization of water supply costs.

In the following sections, two major issue areas are covered: methods of cost allocation, and water supply cost analyses.

METHODS OF COST ALLOCATION

This section reviews the issues surrounding the problem of cost allocation. Familiarity with this method provides a better understanding of the types of costs involved in water supply public utilities, and how they are related.

The basic principle of an allocated cost method is the "equitable" distribution of costs to specific functions and customer classes. Equity here is not similar to an economic concept of equity, where income distribution becomes important. Rather, it refers to economic efficiency where the price paid approximates the cost incurred. The American Water Works Association suggests two methods of allocating cost in their manual of water rates.[3] One is the commodity-demand method; the other is the base extra-capacity method.

Under the commodity-demand method, costs are divided into three functions -- demand costs, commodity costs, and customer costs. The three components of the commodity-demand method are easily classified into fixed or variable costs, which are traditional economic cost concepts. Demand costs represent fixed costs, while commodity and customer costs comprise variable costs. Customer costs are variable, since they cease if output stops. Demand costs are directly related to the cost of providing system capacity to meet peak demands (i.e. maximum day, peak hour, or maximum week). This includes plant as well as operating expenses. Fire protection costs may also be covered in this category. Commodity costs vary directly with the quantity of water produced and sold. This involves the costs of power, chemicals, and other operating and maintenance expenses connected to the amount of water supplied. Customer costs consist of expenditures on meter readings, billing, accounting and collecting, meters, and maintenance of

customer related equipment (billing machines and meters). Those costs vary with the number of customer accounts, but are independent of the water produced or the demand rate.

The commodity-demand method is one approach to the allocation of utility costs to specific functions. The other prominent method is the base extra-capacity method. R.L. Greene notes that his breakdown "is the one generally accepted in the field."[4] All costs are again divided into three components: customer, base, and extra-capacity. In the base-extra capacity method, the three components are not easily classified as fixed or variable. Customer costs remain variable as before, but base and extra-capacity costs both contain fixed and variable elements. This results from the use of average daily demand as the demarcation between base and extra-capacity. The definition of customer costs is the same as for the commodity-demand method. Base water costs are the costs associated with the quantity of water demanded and the operation, maintenance, and capital costs of servicing the average daily demand on the system. The average daily demand is identified as a 100% load. In this component, operating costs are joined with capital costs, while only operating costs comprised the commodity component above. Extra capacity costs consist of the costs to meet use requirements above the average 100% load. It includes capital and operating costs for additional system capacity beyond the average, such as the maximum hour or day. Fire protection costs may also be included.

Once costs have been allocated to the correct functions, the proper assignments to customer classes remain to be determined. Briefly, allocation of capacity or demand costs to customer classes are decided primarily on the basis of ratios of peak demands to average demand. The major customer

classes are residential, commerical, and industrial users. Sometimes, special cases are considered such as hospitals, schools, government buildings, and welfare cases, but they are ignored here. Commodity or base costs are distributed according to the volume of water used. Customer cost allocation, though depends on the number of customers or meters. The AWWA theorizes that equity as approximated by a rate structure attempts to recover costs allocated in this procedure.

Linaweaver and Geyer, in a study on residential water use, appear to promote the base extra-capacity method.[5] They discuss how part of the Johns Hopkins University Water Research Project is attempting to gather data on peak use by customer class which may prove useful in the allocation of extra-capacity costs. But, they do question one point in this type of allocation namely, the use of average annual consumption in determining the proportion of plant investment to be allocated to base capacity.[6] Average daily use fluctuates around average annual use. During the winter, average daily use is lower than the average annual use; but it is higher during the summer. Rather, Linaweaver and Geyer suggest the use of domestic water requirements, average daily winter demand, to determine base costs. Also, sprinkling demand can be identified and used for the extra-capacity cost allocation. As far as residential water demand is concerned, this seems more equitable than use of average annual demand for cost allocation.

Another proponent of the base extra-capacity cost method is W.L. Patterson.[7] His article on water rates in 1962 is widely quoted as the major article in this field. Patterson provides an extensive example of cost allocation, using the base extra-capacity method to allocate system costs and the noncoincidental extra capacity method to distribute peak use costs to customers class.

A noncoincidental method implies that the peak characteristic (ratio of maximum use to average annual use) of each class be examined. The term, noncoincidental, signifies that the ratio of peak to average is not related to the time of the system peak. If a certain customer class did not consume during the system peak time, but was characterized by a high ratio of peak to average use at another time, then part of the system capacity costs would be allocated to that customer class. Patterson notes that:

> "This method of allocation most equitably distributes costs among customer classes whose individual maximum demands would not necessarily occur simultaneously or at the time of the system peak."[8]

The actual degree of equity in this and other forms of peak load cost allocation is an issue that has received much attention in the literature.

Davidson, in his book on price discrimination, devotes a full chapter to all the proposed methods of capacity cost allocation.[9] In brief, he demonstrates that all twenty or more methods, including the noncoincidental method, possess varying degrees of discrimination. One or another group of customers can force a reallocation of costs from themselves to others by adjusting their demand loads, even though their load contributes to the system peak. As a result, the noncoincidental method is shown to increase discrimination among users if rates are based on such a cost allocation.

Davidson applies the commodity-demand method in his analysis, but adds one important point: the relevant costs. The relevant cost concept

> "...is not the export accounting record of costs incurred in producing, distributing, and selling the (commodity) purchased by

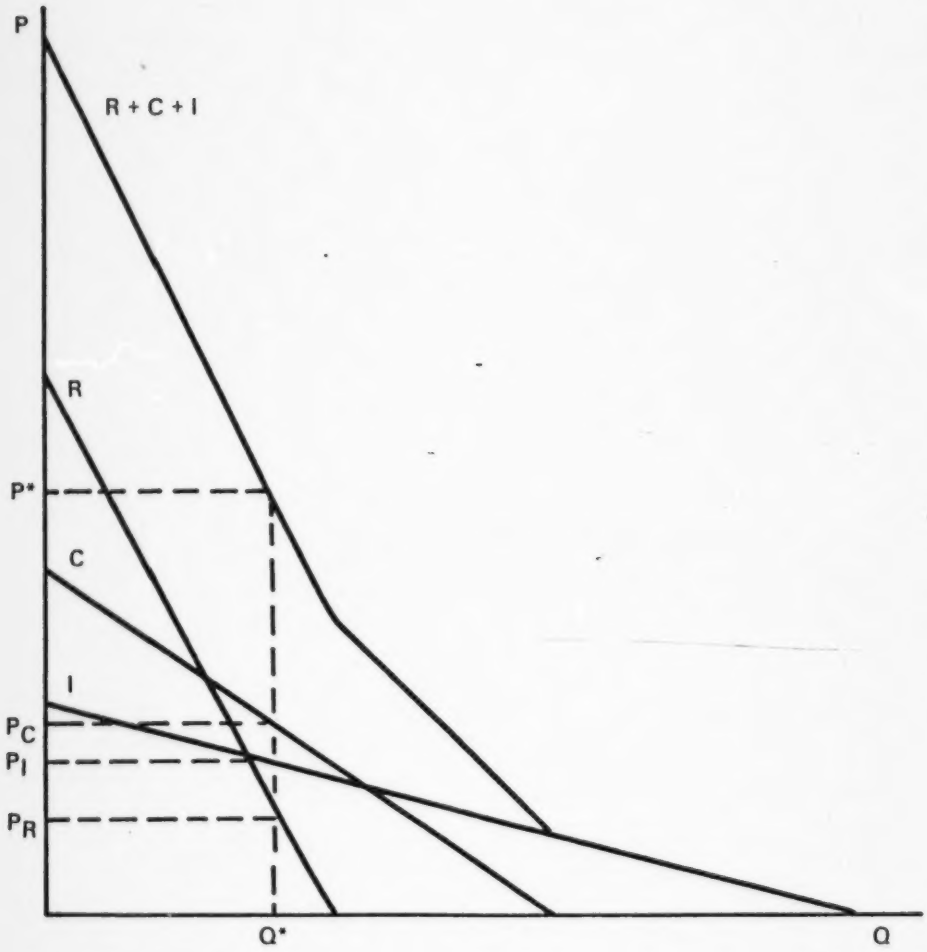
the consumers in a period just past. All attempts to ascertain unambiguously total costs, or average costs per unit of output from expost accounting records encounter insuperable difficulties in the allocation of fixed costs, common costs, and joint costs; these costs are arbitrarily allocated, if they are allocated at all. This particular problem of allocation of fixed, common, or joint costs is not encountered in finding marginal or incremental costs, but it is also true that marginal or incremental costs cannot be determined from usual accounting records. The usual accounting records are records of the past and the relationship with which economists are concerned are the expected or anticipated relationships--a matter of the future."[10]

Marginal or incremental costs, if possible to determine, are the relevant costs. Davidson theorized that the important elements to be defined are the additional costs incurred if another unit of output is sold, the incremental cost of an additional unit of capacity for peak load demand, and the marginal cost of another customer served by the system. Employment of these definitions of costs would improve resource allocation and avoid some of the problems of a strict cost allocation.

Davidson also mentions the problem of allocation under conditions of joint and common cost. Though not directly discussed by Davidson, other articles have elaborated on it. Greene criticizes Patterson's work and discusses the problem of joint cost.[11] He argues that the ratio (noncoincidental) method of cost allocation used by Patterson favors large quantity users more than other users, since the larger ones have a higher average hourly use than the smaller customers. It also tends to penalize users,

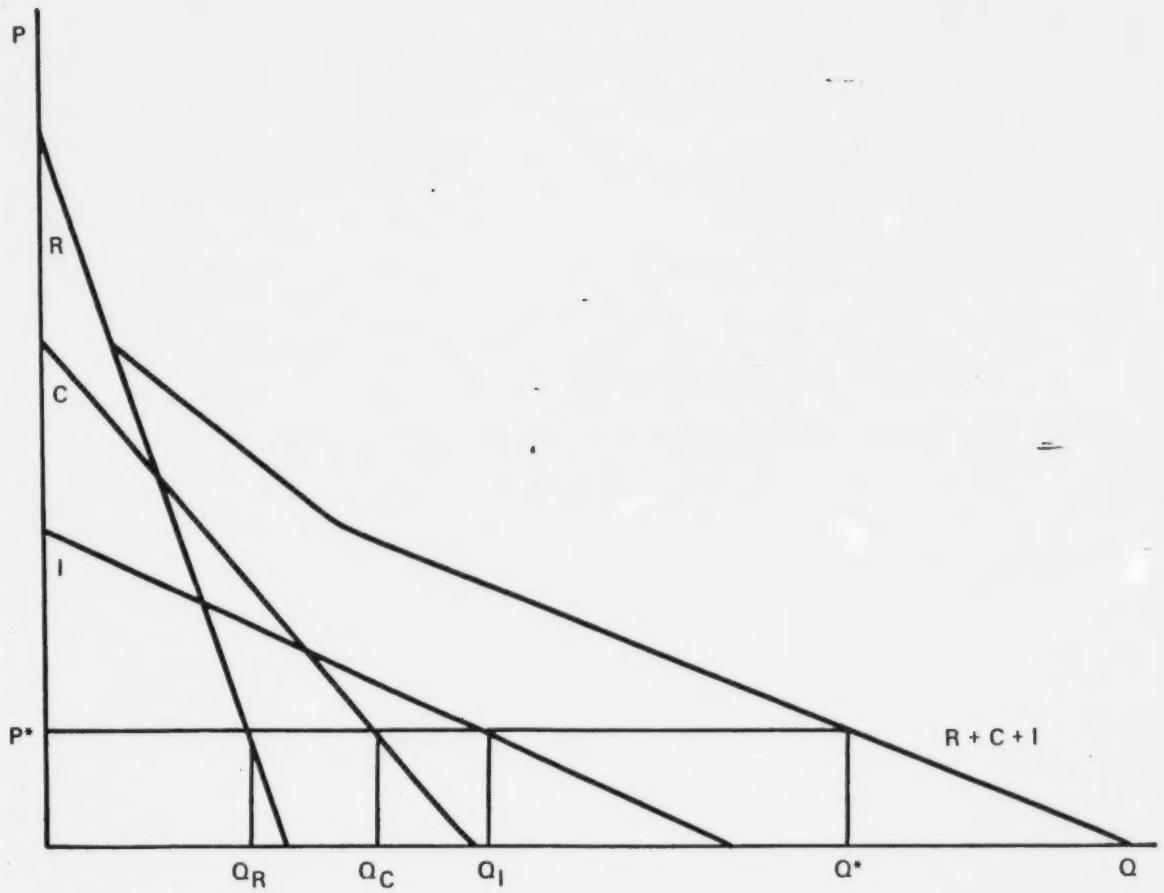
with or without a peaking characteristic, who do not take water during the the system peak. A cost allocation based on Patterson's method would distribute cost on the basis of differences in demand characteristics rather than differences in costs imposed by the various user classes. This does not lead to an equitable allocation if rate differentials are based on this allocation.

According to Greene, the cost allocation methods were derived because of the joint cost conditions between peak and off-peak conditions. Capacity costs are joint costs if the cost of producing the services (joint products) is rendered at different periods of time.[12] Time jointness is the correct term. Capacity which is used to meet a peak demand, is also available for off-peak use. Services produced at those different times are true joint products because capacity cannot be adjusted. Greene points out that the utility solution to joint cost conditions (Patterson approach) implies that the distinct customer class demands are summed vertically, (Figures 1 and 2), to determine the distribution of costs to each consumer group on the basis of relative demand strengths. The vertical summation requires that each class be allocated a different per unit cost of capacity, depending upon the relative heights of their demand curve, even if the customer classes were to consume identical quantities of the commodity in the same time period. If the demands were summed horizontally, as in Figure 2, the same per unit charge could be allocated to each customer class, but the total cost allocated would vary because the quantity consumed by each group in the same time period is not the same. It would depend on the demand curve of each separate class. This is a more realistic description of the peak-load situation when characteristics of consumer classes are considered.



Q* = plant capacity.
P* = weighted average $P_C + P_R + P_I$
R = residential demand curve.
C = commercial demand curve.
I = industrial demand curve.
P_R = residential price.
P_C = commercial price.
P_I = industrial price.

Figure 1. Vertical summation of demand curves.



Q* = plant capacity
P* = price per unit
Q_R = residential demand at price P*
Q_C = commercial demand at price P*
Q_I = industrial demand at price P*

Figure 2. Horizontal summation of demand curves.

The principle foundation to Greene's argument is the distinction between joint and common costs. Greene states,

> "There is no justification for charging different users, in the same time period different rates for the same quantity of service, since the costs are common costs and not joint costs. . . . any difference is discrimination based on criteria other than economic efficiency criteria."[13]

Wallace presents, in a rather lengthy discussion, the distinction between joint and overhead costs (common costs). Briefly, he argues that in the case of joint supply, productive capacity available is fixed in proportion to the demands of different customer groups. An entrepreneur cannot increase or decrease his output capacity in one market without affecting the capacity available in another market.[14] This is similar to the situation of a water works. Capacity available to handle peak-load operation is available for off-peak periods.

But, if capacity may vary in relation to the demands of different customer groups, cost is common. For services produced with common cost, no element of jointness, uniformity in rates is appropriate. This may occur in a water utility when many consumers exercise demands at the same point in time. As a result, under condition of common cost, allocation to consumer groups cannot be made, because cost is not related proportionally to the different groups. For correct analytical results, Wallace promotes long-run marginal cost as the relevant dimension to study.

The basic issue of joint costs revolves around the time period in which output is consumed. Time jointness refers to the fact that capacity cannot be adjusted to meet changing demand. Peak demand is responsible

for the amount of capacity available. Off-peak demand is serviced with excess capacity. Therefore, cost should be allocated differently between these periods. An off-peak unit, consumed by a residential customer, costs differently than a peak unit.[15,16,17] As a result, cost allocation, according to Greene, Wallace, and Bonbright, should depend on the time jointness of the costs. Changes in demand rates require different cost allocations between peak and off-peak regardless of the relative strengths of demand at a given point in time by each customer class. Once the peak has been reached, the capacity cost per unit of output is the same whether a residential, commercial, or industrial user consumes the service.

> The issue of cost allocation still remains. Bonbright notes that "... the main reason for difficulty with the full-cost apportionment method lies in the special character of the only costs that can be allocated, on a cost causation basis, to specific quantities of specific types of service."[18]

The costs that are allocable are of necessity the differential, incremental, or marginal costs. Bonbright also points out that only rarely would these costs sum up to total operating and capital costs.[19] Other cost allocation deficiencies discussed by Bonbright are the inability to define fair value of capital, investment for peak load allocations, the failure of the cost analyst to allocate all costs to three or four categories, and the poor handling of joint cost issues by the cost analyst.

Like Wallace and Davidson above, Bonbright favors an estimation of the long run marginal costs to service different classes and a formula apportionment among the classes for all unallocable residues of total cost.

This could free the analyst from pressure to divide up all the costs, even though there would still be problems in finding a rational method to apportion the unallocable residual costs. Bonbright concludes that:

> "The really important analyses are not those which attempt to apportion total capital and operating costs among the different classes or units of service. Instead, they are the analyses designed to disclose differential, incremental, or marginal, or escapable costs--costs which are not ordinarily derivable from total costs and which cannot be added together so as to equal this total."[20]

In their excellent book on water supply, Hirshleifer, DeHaven, and Milliman also discuss the issues involved with a cost allocation method. They argue that because of the existence of joint costs, there is no unique way to segregate total costs into three components: customer, commodity, and capacity. According to these authors:

> "This is logically equivalent to the impossible task of dividing sheep costs into wool costs, mutton costs, and hide costs. A new reservoir, for example, may at one stroke increase system capacity, permit connection of a new class of consumers, and lower unit costs of delivering the commodity."[21]

With regard to capacity allocation, Hirshleifer, DeHaven, and Milliman, believe that capital costs cannot be correctly divided between the various service dimensions represented by capacity and commodity. Any attempt to do so, as exemplified by the Water Rates Committee of the AWWA, is defective in theory and inconsistent in application.[22] This also applies to the general classification of costs under the commodity-demand method.

Their alternative is identical to that offered by Davidson, Wallace, and Bonbright. The relevant dimension to examine costs is the marginal cost: the cost of adding another customer with capacity and commodity elements constant; the cost of adding a unit of capacity with customer and commodity elements constant; and the cost of increasing output by one unit with customer and capacity elements constant. Those costs are measurable and more relevant for rate purposes. In another article, Milliman points out that:

> "Pricing according to incremental costs, water rates that reflect true economic scarcities, must become the order of the day if we hope to deal with the problem of water supply in the future."[23]

In general, this discussion on allocation of costs has attempted to outline some of the problems associated with current practices in use and the correct way to examine costs. Though there has been no final solution to the issue, the present state of the literature appears to favor the Davidson, Bonbright, Wallace, Hirshleifer, DeHaven, and Milliman analysis of costs to the AWWA or Patterson approach because of the latter's misinterpretation of the joint vs. common cost issues.

WATER SUPPLY COST

This section reviews existing literature on water supply cost functions and analyses. In estimating statistical cost relationships, two different approaches stand out as the most significant.[24] One is a factor-cost approach; the other is an explanatory variable approach.

The factor-cost approach develops a statistical relation between total cost and the price and quantity of the factors employed. This type of cost function can be defined if the production relation, quantities of inputs, and prices of inputs are known. One major difficulty with this method is

the identification and estimation of the production relation. Also, the cost function developed tends to be more of an accounting relation than an economic one.

The other method is an explanatory variable approach. This method attempts to estimate the statistical relationship between cost and certain key explanatory variables. A general functional relation is theorized, the specific form of which is determined by the interdependencies among the variables. A functional cost relation can be stated as $c = f(x)$ or $f: x \rightarrow c$ where c is cost (total, average, or marginal) and x is a vector of explanatory variables and shift parameters. The form may be linear or nonlinear. The statistical relation does not attempt to examine cost in actuality for accounting purposes. Rather, the explanatory variable approach tries to identify the inter-relationships that exist to improve predictive and explanatory capability. This is the direction that this discussion will follow.

Three major categories exist in the literature on water supply cost. They are treatment, total cost, and transmission cost. One brief look at peak-load cost will be included, but it is not as important because no articles appear to concentrate on peak-load cost estimation.

Total Cost

This section reviews the existing literature on total costs of water supply. Total cost of water supply suggests two major divisions: treatment and transmission/distribution. Briefly, treatment involves purification of water; and transmission/distribution consists of finished product transportation to the consumer.

The difficulty of analysis on total cost arises in correctly identifying variables that are related or explain the variation in costs. Coase, in his

article on uniform pricing systems, examines the shape of the supply and cost curves when the same price is charged for a product or service over a given area, even though the cost of supply may vary from one part of the area to another.[25,26] If a public utility is to be self-supporting, and a uniform price is adopted, then according to Coase:

> "...the additional costs of supplying certain groups of consumers exceed the receipts obtained from those consumer, the difference will have to be made up by additional payments from other groups of consumers."[27]

In his discussion, Coase assumes that the marginal costs of supply to each consumer rise with an increase in distance from the plant and that the marginal costs of supply to each individual consumer are constant at a given distance from the production source. As a result, the shape of the cost curve depends upon the quantity consumed by individuals at various distances from the plant. This is exemplified in Figure 3.[28] Line (1) would be obtained if consumer demand at each cost/distance level is relatively large compared to that in line (2) or line (3). Total cost can be dependent upon many factors. Coase points out two: quantity supplied and distance. Even through the price charged appears to affect the shape of the cost curve, it is the marginal costs at each demand level, not price, that are important. Other explanatory variables are used in several empirical studies.

L. Hines attempts to estimate a long-run cost function based on a cross-section sample of Wisconsin community water supply systems.[29] Since a long-run cost function is estimated, certain issues must be handled. Equipment and operating costs must be converted to the same price level using a cost index. The adjusted capital expenditures have to then be depreciated at a rate reflecting the remaining capital value. Estimates of capacity are

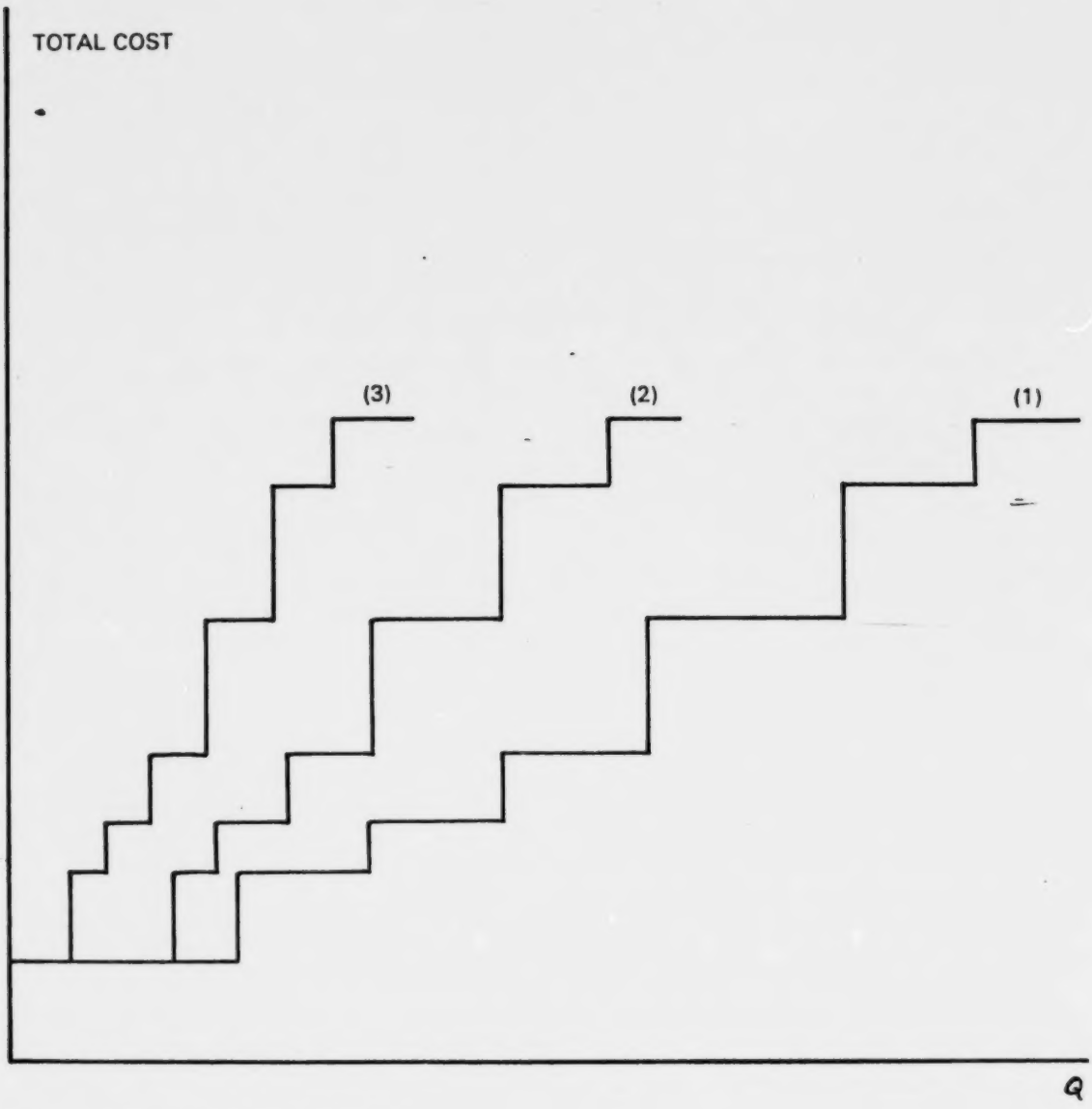


Figure 3. Step cost functions.

necessary to make comparisons among different installations, because one plant operating near capacity may have lower per unit costs than one producing lesser capacity. A competent measure of scale is very difficult to obtain.

Hines estimates the relationship of cost to per cent capacity utiliztion (% C_u) and adjusted plant investment (API) for three production classes: surface water supply, ground water supply, and ground water supply with partial treatment. Two cases in each class are specified with respect to adjusted plant investment: API_1 = historical plant cost adjusted to the 1957 price level; and API_2 = historical plant cost less power and pumping plant adjusted to the 1957 price level. Hines justifies this demarcation because:

> "There is more nearly continuous capital addition to the transmission and distribution part of the system than that of power and pumping equipment, and the capital change in the former is more directly related to the number of customers served by the water facility."[30]

The results obtained using API_1 were not significant at the .05 level. However, when API_2 is used, the hypothesis of constant costs must be rejected because the coefficients are significant at the .05 level for surface and underground water supply classes.

A more detailed and precise attempt to estimate water supply costs was made by Ford and Warford.[31] Their work tries to explain unit costs in the water supply industry. On the basis of a cross-sectional sample for a given year, Ford and Warford estimated the long-run average total cost curve for water supply. Costs are defined as the sum of expenditures on sources of supply, transmission of water, and treatment of water.

The functional forms employed and used as regression equations are linear, quadratic, and exponential with a logarithmic or semi-logarithmic

transformation. The key explanatory variables chosen for estimation of the cost function are Q (daily supply in thousands of gallons), AREA (area in square miles), and Q/AREA.[32]

These results were obtained from the equations:

1. As Q/AREA increases, cost decreases; this signifies the existence of economies of scale in water supply.

2. Holding Q constant, as AREA increases, costs rise, but at a decreasing rate.

3. Holding AREA constant as Q rises, average cost falls, but at a decreasing rate.

Thus, use of Q, Q/AREA, and AREA give some indication of the relation between area serviced and cost incurred. The cost of transmission is obscured because cost is examined in total and not disaggregated into major components. Therefore, the degree of existence of economies of scale as estimated may be misleading. Also, a cross-sectional study can indicate economies of scale at one point in time; but, there may be vast differences in the operating method or management of a utility in the sample which could bias the measure of returns to scale.

In general, the article is methodologically correct and statistically significant in terms of results. But, the R^2 values were not very high. Ford and Warford offer two conclusions on this subject:

> "Either (a) we should break down costs into the production costs of the textbooks and seek to explain these by using our independent variables; or (b) the technological and natural diffierences that do exist between the various water undertakings in the industry-the unquantifiable variables-must be such as to rule out the existence of a so-called long-run cost curve for the industry; such technological differences between areas must swamp the independent variables we have used".[32]

Their latter conclusion may not be too important because the level of technology employed in the water supply industry is fairly equal at one point in time except where extreme age differences exist or where ground water vs. surface water differences exist which are not embodied in the model. Other articles dealing with the total cost issue are by Griliche,[36] McElroy,[34] Bassett,[35] Scarato,[36] Moore,[37] and Andrews.[38]

This discussion on total costs has attempted to present the relevant analysis to date on statistical cost estimation and existence of economies of scale for water supply systems. Most studies estimated cost as a function of a design capacity or average daily flow. Other analyses added different explanatory variables, such as area, population, and number of customers. Relationships between cost and these variables give indications of the degree of economies of scale with respect to market area. Existing empirical studies do not adequately deal with this issue. That economies of scale are achieved in treatment and total cost is generally accepted. But, further analysis should attempt to delve into the demarcation between treatment and distribution cost in relation to economies of scale.

Treatment Cost

Two main elements which comprise treatment cost are analyzed. One is construction or capital cost; the other is operation - maintenance cost. Orlob and Lindorf examined treatment cost to determine its relationship to the costs of surface water importation, reclamation of waste waters, ground water recharge, and any other alternatives available for increasing water supply to California.[39] Their study consists of a cross-section of 32 treatment facilities as existed in 1956 in California. All construction cost data was adjusted by means of a water treatment plant construction cost

index. Based on the Engineering-News Record Construction Cost Index and the Marshall and Stevens Equipment Cost Index, Orlob and Lindorf developed their own index for the Pacific Coast States. The plants included only those with complete treatment.[39]

Construction cost was theorized as a function of the explanatory variable, design capacity. In general, the form of the equation would be:

$$C = \alpha Q_n^{\beta} \qquad (1)$$

where

C = total captial cost of a complete water treatment facility;

Q_n = the design capacity of the plant in million gallons per day (MGD); and

α = intercept

β = elasticity of total cost with respect to design capacity.

Estimation of the equation generated the following relationship:

$$C_c = 257\ Q_n^{0.67} \qquad (2)$$

The value of $\beta = 0.67$ implies that economies of scale may exist in treatment plant construction. If "t" statistics were provided, it would have been possible to test whether β is significantly different from one. Since the relevant statistics are not available, no conclusion can be made concerning economies of scale.

Operation and maintenance cost is assumed to be related to average daily flow in million gallons per day in the same functional form as construction to design capacity above. The statistical relation estimated by Orlob and Lindorf is:

$$C_o = 68.4\ Q_a^{-0.41} \qquad (3)$$

where

C_o = the cost of operation and maintenance (including labor, chemicals, power, and plant overhead): and

Q_a = the average daily flow, MGD

This is the average cost function, not total cost. The dimension of C_o is \$/million gal. When converted to total cost equation 3 becomes:

$$C_t = 68.4\ Q_a^{0.59} \qquad (4)$$

where

C_t = total cost in \$/day

Since $\beta = .59$, economies of scale may also exist in the operation and maintenance of treatment plants.

The importance of this work is not the statistical merit, but the fact that it is one of the first attempts to estimate the costs of water treatment. The authors ignored discussion of the issues of economies of scale and instead, concentrated on determining the relation of treatment costs to the production costs of all plausible alternatives for water supply expansion. As a result, important economic issues were not examined.

In a more recent article, Koenig further investigates the area of water treatment cost estimation.[40] He attempts to provide a detailed analysis of the physical characteristics, operating data, and costs of a water treatment plant. Once the information is presented in a standardized form, comparisons may be made between plants. The class of water treatment plants studied by Koenig differs from those examined by Orlob and Lindorf. Koenig included those plants having coagulation, sedimentation, and rapid-sand filtration. Orlob and Lindorf include the chlorination process in their plant description.

The general objective of Koenig's study was to identify the relevant costs of water treatment and their proportional contribution to total cost. The purpose was to provide data and information to decision-makers, such as

utility managers, engineers, planners, and economists, and to aid in cost-benefit analyses.

This study is based on the cost engineering audits of 30 water treatment plants as of 1965. The sample data is a representative cross-section of water purification plants. The methodology employed is similar to that used by Orlob and Lindorf in that a cost index was used to adjust investment expenditures to one common year. But Koenig expanded his study to examine in detail specific treatment costs such as: chemical, filter, energy, heating, and manpower costs as well as capital expense. With respect to investment expense, Koenig estimated an equation similar to the one Orlob and Lindorf used. The only difference is that Koenig's is an average cost relation. He finds that:

$$C = 30.7\ Q_d^{-0.323} \qquad (R = 0.77) \qquad (5)$$

where

Q_d = design capacity; and

C = cost, ¢/gpd.

Equation 5 is significant at the 0.001 level. The Orlob and Lindorf total capital cost relationship when converted to an average cost function became:

$$C_a = 257\ Q_n^{-0.33} \qquad (6)$$

where

C_a = average cost in $/mgd

The value of the exponent of Q is nearly equal in both. Koenig continued his analysis by adding Orlob and Lindorf's data to his. The combined regression provided a correlation coefficient of 0.57 and a line flatter and below the line estimated from Koenig's data alone. The difference, according to Koenig, is the several small plants with exceptionally low investment costs which were included in the Orlob-Lindorf study. As a result, their data was dropped in Koenig's subsequent analyses.

Instead of estimating an operation-maintenance cost equation, Koenig estimated average total cost for complete treatment for different utilization ratios. A utilization ratio, $\overline{U}$, was defined as the ratio of average raw water intake in MGD, Q, to the design capability for raw water in MGD, Q_d. Total costs were computed for each plant at $\overline{U}$ = 0.2, 0.5 and 1.0, the Q_d lines in Figure 4. A statistical regression was then performed relating $\overline{Q}$ and unit total costs at each $\overline{U}$ value to derive the $\overline{U}$ lines in Figure 4. All showed high correlation coefficients, but unfortunately, Koenig did not provide the parameter estimates or the specific form of the regression. The Q_d lines in Figure 4 resemble short-run average total cost lines and the $\overline{U}$ lines resemble long-run average total cost lines. From this, one can roughly estimate the total treatment costs of various size plants and average daily flows.

An interesting factor that Koenig fails to point out is the existence of economies of scale. His regression line of investment costs and the functions estimated, as shown in Figure 4, both point to the existence of positive economies of scale in treatment plant investment and operation-maintenance. He discusses methods of cost reduction and the contributions to cost of such key inputs as manpower, but appears to have ignored any discussion of economies of scale. This probably can be attributed to the fact that Koenig's objective was to improve data acquisition and estimation of treatment costs and not to investigate for economies of scale.

One other article examines treatment cost. Hinomoto estimated unit and total cost functions for water treatment based on Koenig's data.[41] A formula is developed to estimate the total annual cost of surface water from seven regression equations analyzing the major factors of water treatment: capital investments, chemicals, pumping energy, heating energy, manpower, maintenance and repair, and miscellaneous. Non-linear functional forms of

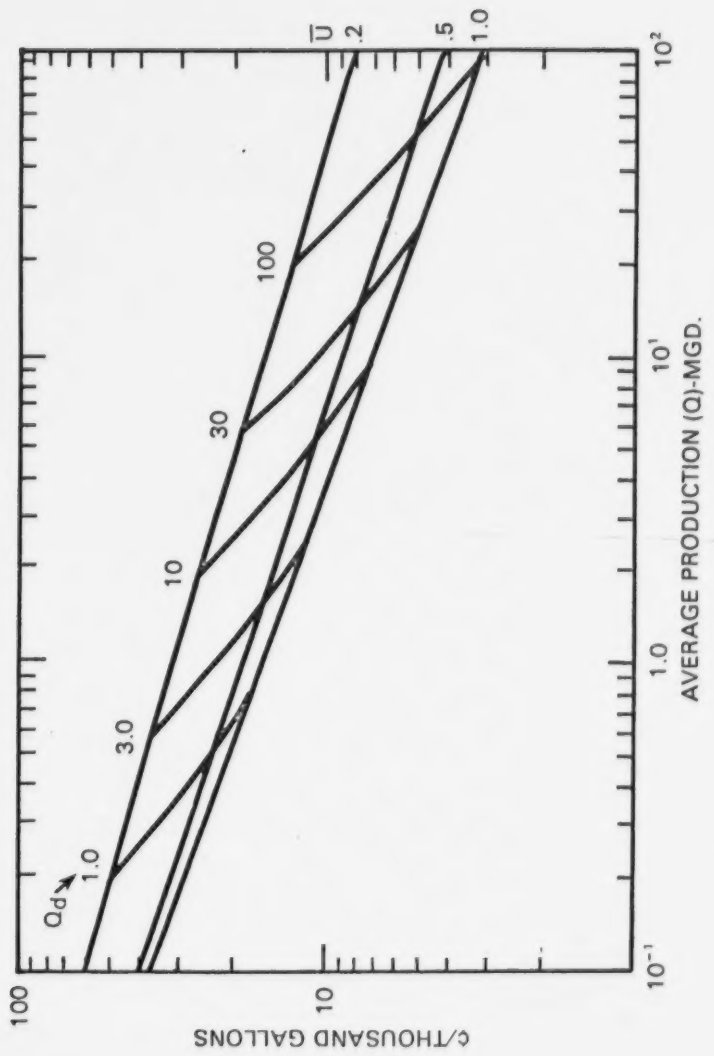


Figure 4. Median total cost of treatment.

the type $C = \alpha K^{\beta}$ (total cost) or $C/K = \alpha K^{\beta-1}$ (average cost) are specified for all seven equations. A logarithmic transformation was performed to permit linear estimation of the regression relationship. The estimated unit cost functions obtained are:

Capital Investment	$= U^{-1}*81.9SK^{-0.325})$	(7)
Chemicals	$= 1.20\ K^{-.236}$	(8)
Pumping Energy	$= 2.78\ K^{-.282}$	(9)
Heating Energy	$= U^{-1}(.307K^{-.519})$	(10)
Manpower	$= U^{-1}(2.73K^{-.313})$	(11)
Maintenance and Repair	$= U^{-.5}(.405K^{-.421})$	(12)
Miscellaneous	$= U^{-1}(.102K^{-.07})$	(13)

where

U = the daily use rate, output divided by design capacity;

S = the annual amortization factor (function of plant to be depreciated); and

K = design capacity.

Hinomoto combines all seven equations to define a total per unit cost equation for a treatment plant. Therefore, given a K, S, and U, the total unit cost can be obtained.

Again, no mention of economies of scale is made. Also, Hinomoto points out that he obtained results very close to Koenig's which is not surprising since he used Koenig's data and methodology. The merit to Hinomoto's analysis rests upon his rigorous use of the U variable.

In general, treatment cost studies have concentrated on estimating the relationship of cost to design capacity and improving the generation of data for better decision making. The Orlob-Lindorf study began the analysis of

treatment cost with a simple relationship. Koenig improved the structure of the analysis by incorporating the utilization factor. Hinomoto extended the use of the U in his set of statistical equations. The next step to be taken in this field appears to be the estimation of costs on a process oriented basis. Instead of estimating the costs of each input, estimate a relationship between cost of flocculation or filtration with respect to a key explanatory variable.

Transmission Costs

The cost of water transmission consists of capital expenditures for pipeline, pumping stations, and storage facilities; and operation-maintenance expenses of which energy cost is a major element. Before reviewing the transmission cost studies, a short description of engineering hydraulic factors involved in water transmission will be presented.

Physical Factors Affecting Costs

Total dynamic head is the major element involved in water transmission engineering. It consists of three major elements: static head, velocity head, and friction head. The importance of total dynamic head rests upon the fact that power or energy consumption per unit of water is directly related to the degree of head existing in the system. Head can be defined as the pressure in pounds per square inch or as the number of feet of liquid which could exert an equal pressure on the horizontal surface at the bottom of a pipe. The height of the column of liquid producing the presssure is known as the head on the surface.

The height of a column of liquid is often termed the static head on the inlet or outlet of a pipe. It is the difference in elevation and is expressed as a certain number of feet. Total static head equals the vertical difference, in feet, between the supply level and the discharge level.

Velocity head refers to the kinetic energy possessed as the liquid moves through a pipe at any velocity.[42] It is the distance through which the liquid must fall to acquire a given velocity and is found from $H_v = V^2/2g$:

where H_v = velocity head, feet of liquid;

V = liquid velocity, feet per second; and

g = acceleration due to gravity, 32.2 ft. per sec.^{2}

Friction head is also measured in feet. It is the equivalent head required to overcome the resistance of the pipe, valves, and fittings in the pumping system. Friction head is related to the liquid flow rate, pipe size, type of pipe, viscosity of fluid, and interior condition of the pipe. Friction head loss varies roughly with the square of the flow for a turbulent system and directly for laminar systems.[43] Once the particular friction characteristics are determined, a system friction curve can be derived which plots head vs. capacity, Figure 5. The combination of static head, the system friction curve, and any pressure differences creates a system head curve, Figure 6. The system head curve can be used for examination of design characteristics in the transmission works. One issue that has received a lot of attention in the literature is the measurement of head loss and the key variables associated with it. Many approaches to the head loss measurement problem have been offered.

Hicks and Edwards discuss one method in their book on pump application using the Darcy-Weisbach formula is shown below:

$$h = f\, LV^2/2gD \qquad (14)$$

where

h = friction head loss, feet of liquid pumped;

f = friction factor

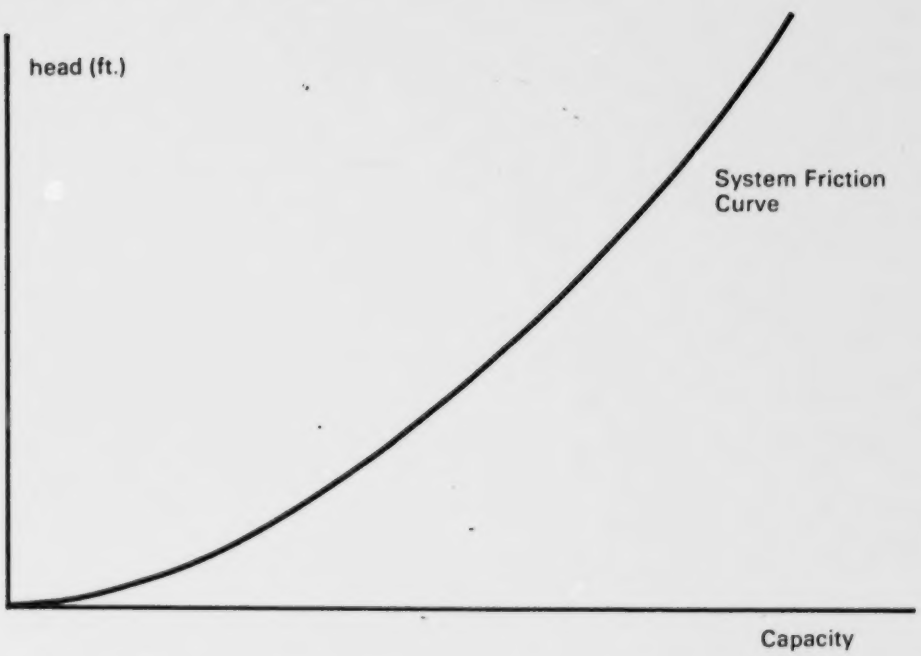


Figure 5. System friction curve.

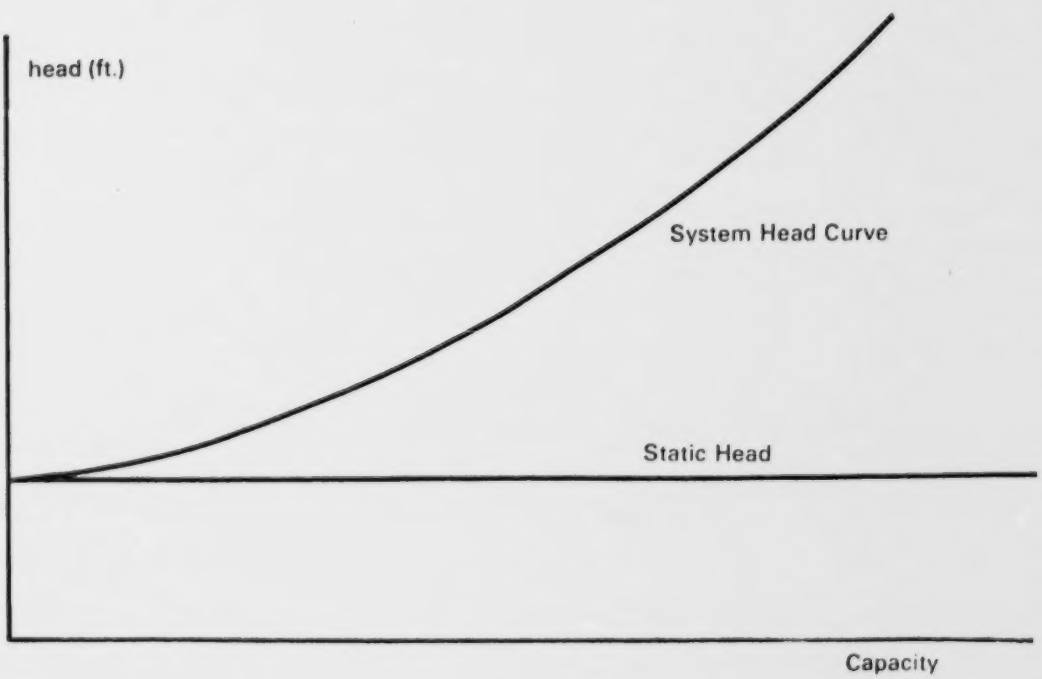


Figure 6. System head curve.

V = average velocity in pipe, feet per second;

D = internal diameter of pipe in feet; and

g = 32.17 feet per second squared

L = length of pipe in feet

This is an engineering relationship. Given D, L, V, and a calculated f, h (friction head loss) can be determined.

An other formulation of headloss measurement is the Bernoulli equation as presented by Hey.[44,45] It is the most complete equation because it includes not only static and friction heads, but also velocity and pressure differences. Hey expresses it as:

$$E_p = Z_i - Z_o + P_i/\gamma - P_o/\gamma + V_i^2/2g - V_o^2/2g + HL_{O-i} \qquad (15)$$

where

E_p = total dynamic head in feet between points O and i;

Z_i = elevation of point i, feet;

P_i = pressure at point i, pounds per square foot;

γ = specific weight of water, 52.4 lbs/ft.^{3};

V_i = average velocity at point i, feet per second;

g = gravity constant, 32.2 feet per second squared; and

HL_{O-i} = headloss due to friction between points O and i.

HL is measured by the Darcy-Weisbach or Hazen-Williams equations for friction head measurement as described previously. The Bernoulli equation is the most comprehensive and complete model for analysis of headloss. All the relevant factors are incorporated. It is complex, but accurate. Use of the Hazen-Williams charts for estimating the C coefficient has reduced the difficulty in the use of the Bernoulli approach. Those charts can be found in many water supply engineering books.[46] In any event, a competent examination of system head curves, friction headloss, pressure variations, and velocity differentials

must use the factors employed in the Bernoulli equation to develop the correct results whether it is an engineer working on transmission optimization, or an economist analyzing the marginal cost differences of water transportation.

Capital Cost

With regard to water transmission cost, two components are important: capital and operation-maintenance cost. Capital costs of water transmission consist of the construction cost of pumping stations and pipelines. Storage facilities are not included because they are built for peak-load demands. Operation-maintenance costs include energy and repair costs incurred in the transmission of water.

Pipeline capital cost was estimated by Ackermann in a technical letter for the Illinois State Water Survey.[47] All cost figures were indexed to the 1964 cost level by means of the Handy-Whitman Index of Water Utility Construction Costs. Ackermann estimated an exponential relationship between construction cost and pipe diameter:

$$Cp = 2.16\ D^{1.2} \qquad (16)$$

where

Cp = construction cost for a transmission line in dollars per mile;

D = pipe diameter, inches

The results suggest diseconomies in per mile construction costs as the pipe diameter increases. Linaweaver and Clark also estimated a similar relation between cost and diameter:[48]

$$K = 1{,}809\ D^{1.29} \qquad (17)$$

where

K = capital cost in dollars per mile; and

D = diameter in inches.

Again, the value of β implies diseconomies exist in the per mile construction costs of pipes as diameter increases.

Both studies estimate cost per mile in relation to pipeline diameter and find diseconomies of scale.[49] Scarato, though, suggests that significant economies of scale exist between capital cost and pipeline capacity. He suggests a function of the type

$$C = f\left[k(\text{capacity})^{\beta}\right] \qquad (18)$$

where

C = total capital cost;

k (capacity) = function measuring capacity

β = parameter which measures the scale effect of capacity on total costs.

Eliassen is mentioned by Scarato as having measured a β as low as .56 which would imply economies of scale with respect to capacity, not diameter.[50] Which is the proper approach, capacity or diameter, remains an unresolved issue. An alternative that might prove useful is to estimate the following relation:

$$C = \alpha D^{\beta 1} L^{\beta 2} \qquad (19)$$

where

C = total construction costs;

D = diameter of pipe in inches;

L = length of pipeline in feet or miles;

and

β1, β2 = cost elasticity parameters

That could provide estimates of the degree of economies of scale with respect to diameter and length. As length increases, eonomies of scale should become prevalent.

Singh presented a complicated approach to pump station cost estimation in his article on water supply systems.[51] The capacity installed is assumed related to the headloss in the system. If head = 300 feet, then the capital cost of a pumping station is:

$$Cp = 17{,}000 + 135\ (P_{300})^{1.01} \qquad (20)$$

where

CP = total cost of a pumping station; and

P_{300} = the installed horsepower necessary to boost the water pressure 300 feet.

Singh does not present any regression statistics on the coefficients, on R^2, or the derivation of his specific functional form. The value 1.01 is definitely ambiguous as a measure of economies of scale. Its relevance to the cost function is not explained. Also, a relationship between cost and capacity is not examined.

In general, there does not appear to be any conclusive evidence for the existence of returns to scale in water transmission capital costs. The articles presented here have investigated specific factors, but have not analyzed or discussed all the relevant variables that may be better associated with capital costs.

Operating Cost

Operation-maintenance cost is the second component associated with transmission costs. The relation between cost and quantity supplied is similar to that theorized by Coase, where the slope of the cost curve depended on the amount consumed at each distance form the supply curve.

Singh presented some theoretical relations between operation-maintenance cost and certain key variables.[52] For pipe-line operation, maintenance, and repair costs:

$$C = 10D \tag{21}$$

where

C = cost per mile; and

D = diameter in inches.

That is a simple linear relation which is not realistic. The cost per mile of pipe usually exhibits economies of scale with respect to diameter.

Energy costs are shown to be a function of static and friction headloss:

$$C = kQ_o \text{ (pf Ho + Ps Hs)} \tag{22}$$

where

C = cost of energy per mile;

K = a relation dependent on the cost per kilowatt-hour and pump efficiency;

Q_o = average yearly demand in gallons per day;

H_o = total headloss per mile of pipline for a constant Qo;

P_s = ratio of actual and constant energy cost spent during the year for static headloss;

and

H_s = static headloss per mile of pipeline.

Singh proceeded through a complex derivation to arrive at the cost function. The function, though, neglects minor variations in the friction factor because he uses Q_o instead of a Q that may vary. This could be an important factor in a residential district with a high peak to average demand ratio.

Singh also sets up a cost relation for pump station operation, maintenenace, and repair cost which is not presented here. It is based on the P_{300} variable noted above, but, Singh does not provide the derivation of this cost function.

In the end, Singh combines all the factors of unit conveyance cost into one equation:

$$C_u = 27.38\ C/Q_o \qquad (23)$$

where

C_u = cents per thousand gallons per mile;

Q_o = average yearly demand in gallons per day;

and

C = total annual cost of conveying Qo through a pipeline of D inches for a distance of one mile.

This suggest that as Q_o increases, C_u decreases. That is an empirical question which has not been adequately analyzed by Singh. Also, use of C_u hides any relevant marginal cost consideration. Singh does provide a graphical analysis of C_u for selected values of Q_o and pipe diameter. But, his equation is derived from a set of seven other equations which apparently are not empirically estimated. It appears that Singh used specific relationships from various articles to derive his cost functions. Those derivations are not adequately explained.

One final article on water transmission costs by Linaweaver and Clark provides a coherent derivation of water conveyance cost functions.[53] It combines engineering and economic considerations into one equation.

Lineaweaver and Clark provided a specific derivation of a general expression relating the principal factors that influence transmission costs to the cost of transporting water. There are two points of interest. First, this equation does not include any consideration of pump station capital cost. And second, the headloss characteristics incorporated do not allow for changes in pressure or velocity as done in the Bernoulli equation. If only short distances are analyzed, the pressure and velocity differentials can probably be ignored.

Transmission costs consist of capital and operation-maintenance expenses. This discussion reviewed the existing literature on measures of headloss and the theoretical and empirical studies of transmission costs. The empirical analyses were not rigorous in nature and the theoretical analysis of Singh was overly complex and unclear. Linaweaver and Clark did provide a competent approach to water transmission costs, but appear to overlook pump station capital cost.

Peak Load Considerations

Peak-load costs are reflected in the cost of storage tanks, greater capacity pumping stations, and larger sized pipelines. The empirical studies that investigated the costs of water supply ignored peak-load cost considerations. Instead, they examined average flow cost relations. This is probably due to the paucity of data on peak-load characteristics. The articles that do examine peak-load conditions usually analyze the trade-off between cost of increased pump capacity vs. increased storage capacity. Schmid points out that:

> "To produce at a greater pumping rate than the peak-day average may necessitate larger transmission and distribution mains and greater investment in booster stations and controls for limited use over the year. To produce at lesser pumping rate than the peak-day average, on the other hand, requires costly additional storage."[54]

Those considerations are important for future cost studies of water transmission systems. It is felt that more competent analysis is necessary in this field.

SUMMARY OF LITERATURE REVIEW

This literature review has attempted to provide a background on certain key issues and factors involved in a water supply cost analysis. The two major areas studied were: methods of cost allocation and water supply cost.

The proper allocation of costs is the important issue in the first area. Many methods have been used to distribute costs, two of which are most frequently used by public utilities. They are the commodity-demand method and base extra-capacity method. Most discussion has centered upon the allocation of peak-load capacity costs to system users. Some authors promoted a distribution of costs based on a noncoincidental demand method. As a result, capacity costs are allocated on the basis of demand characteristics which are the ratios of peak to average use for each customer class. Therefore, those consumers with a high ratio, but no consumption at the system peak, could be allocated a large portion of capacity costs. The proper viewpoint involves the knowledge of the difference between joint and common costs. Joint costs exist when the capacity of a water works is available for use during peak and off-peak periods. Common costs occur if different customer groups consume at the same time at, for example, the system peak. As a result, no rate discrmination among customer classes that consume at the system peak should be made.

One other point concerns the relevant dimension in which to analyze cost. Most authors reviewed suggest that marginal cost is the best concept on which to base decisions. The problem, though, is proper classification and estimation of marginal costs of each component analyzed: customer, commodity or base, and capacity cost.

The section on cost analysis in water supply reviewed theoretical and empirical studies on treatment, total, and transmission cost. Most studies consisted of attempts to empirically relate key explanatory variables to average and total cost. Capacity and per unit utilization were two major variables analyzed.

Attempts were made to estimate the degree of economies of scale in water treatment and the total cost of water supply. The results may be valid, but few studies supplied the regression statistics necessary to determine the significance of the estimated parameters. Also, it is difficult to estimate economies of scale for total cost of water supply. Because of the inherent physical and operational differences between a treatment plant and a transmission system, separate estimation of the components would provide better knowledge of the degree of economies of scale. Combined analysis obscures information valuable for plant investments and expansion decisions.

Transmission cost empirical studies were not rigorous in relating key explanatory variables. Also, theoretical derivations and cost function sepcifications were inadequate. The engineering literature is extremely explicit and significant, but the economic application of engineering relationships needs further analysis.

Future research in this field should concentrate upon identification and estimation of peak-load costs and the marginal costs of each water supply component. Treatment cost has received much of attention, but transmission cost considerations have been largely ignored. Extension of water mains to the fringes of existing service areas will depend on such analysis. Only through comprehensive study of the relevant marginal costs can sound decisions be determined.

DATA COLLECTION METHODOLOGIES

In order to carry out the analysis of cost rate differentials, data is needed on rates, usage/and or consumption, and the costs of delivering any amount of water to specific locations in a water service area.

Water rates are published, and data on usage is obtainable from the account records at most water utilities, but costs are another matter. This section details the specific methodologies employed to obtain these cost estimates. Other sections extend the analysis. This section describes the Cincinnati Water Supply Study discussed in the beginning of this report.

COMPONENTS OF WATER SUPPLY COSTS

To facilitate the analysis, we divide the water supply system into two major elements: (a) acquisition and treatment (A&T), and (b) transmission and distribution (T&D). Both elements of course, contain capital and operating cost components. Support services costs in this analysis will be treated as a constant and fixed cost per customer account. A&T functions occur within the framework of a centralized plant, and T&D in effect from the transportation system (pipelines, pumping stations and storage facilities) for finished water, and as a consequence, a proper economic cost accounting requires separation of these functions.[55]

A&T capital expenditure is determined by the design capacity of the plant. In a given time period, capacity is fixed and the marginal capital cost of another unit of output is zero unless water demand already equals capacity. Once capacity is reached the marginal cost of capital for another unit of output must be included in the cost of production.

However, an important distinction must be made between capital available for peak vs. off-peak periods. In large scale plants, such as a water works, the base or average winter load may represent a significant portion

of capacity. Therefore, capital consumption (wear and tear on capital equipment) can result to a large degree from off-peak use and accordingly that capital cost must be allocated to the average winter demand load. This would not be as important for a system with a very low ratio of off-peak use to plant capacity.[56]

Operating costs of A&T are directly related to the quantity of treated water produced. The marginal cost of operating the plant is not equal to zero regardless of the utilization of capacity; but it may remain constant over large ranges of output for a selected plant scale. Operating costs per unit of output can vary depending upon the economies of operation existing in a given capacity plant.

The combination of capital and operating costs can be useful in examining the A&T cost of peak-load periods and the degree of existence of scale economies. Analysis of returns to scale and costs at the system peak facilitate improved cost allocation.

T&D capital expenditure is determined by the design capacity of pipelines, pumping stations, and storage facilities. Pipeline diameter can be used to relate capital costs to capacity, since the volume of water flow possible in a transmission or distribution main increases as diameter increases. Other factors such as age and interior condition of the pipe are more important in their effect on operating costs, not capital costs. They will be discussed later.

The capacity of a pumping station is measured by the volume of pumped water it can handle during a given time period. To increase capacity, a larger facility and greater capital expenditure is required. This same relationship holds for storage tanks, in that the capacity is dependent upon the total available volume. Storage is utilized mostly during peak-load periods.

The marginal capital cost of another unit of output is zero for pipelines and pumping stations up to the point of capacity. As mentioned before in the section on treatment plant capital cost, however, off-peak demand may be a significant factor in capital consumption. Therefore, a proportional amount of capital cost must be allocated to the off-peak load.

Storage tanks are used only when the pipelines and pumping stations have reached capacity. Therefore, the marginal cost of capital for storage tanks is zero until the system peak-load has been reached. This refers to the point in time when the demand load for a selected service area or the total service area is greater than or equal to the combined capacity of the system-pipes, pumping stations, and storage. It is assumed in this analysis that storage tanks are erected for peak demand periods. As a result, the total storage cost can be allocated to the peak period even though tanks may be utilized during an off-peak period.

Operating costs of T&D, though determined on one major variable--energy, are very complex. A major portion of operating expenditures can be attributed to power consumption at pumping stations. Transportation of water over rough terrain and large distances requires a great amount of energy. Other operating costs such as manpower and maintenance are incurred, but they are not as significant or as directly related to output as energy consumption.

The energy cost of pumping water depends upon the quantity of water supplied, the distance to a demand point, and the net altitude between the demand point and supply point. Other operating expenditures remain relatively fixed with respect to output.

The marginal cost (rate of change of cost) of operation varies over three dimensions: quantity, distance, and altitude. Examination of that relationship is a major concern of this study.

THEORETICAL CONSIDERATIONS

Existing pricing policies can lead to cross or internal subsidizations for users in all of the service areas: pricing inefficiency resulting from inability or refusal to charge consumers on a benefits received basis, may allow substantial intra-area variation in the difference between rates and costs among users. Average net subsidy refers to the difference existing between the price paid and the cost incurred in the supply and demand for water. Three types of user subsidization may occur because of the distribution of costs over the service area and between peak and off-peak periods.

The first is reflected in distance to the customer. A greater amount of energy is required to pump water a long distance, for example twenty to thirty miles, than to supply a customer near to the plant. This is not true of course, if the customer resides at a lower altitude than the plant. In a similar manner, this is applicable to the second factor: topography. Customers served at a higher altitude require larger amounts of energy than those at lower altitudes. The head, (feet), necessary to supply consumers at various altitudes and distances affects energy consumption at the pumping stations. The third factor involves time of consumption. The cost of water supply varies depending upon whether demand occurs during the off-peak load or the system peak-load. Current water pricing mechanisms do not usually take account of such cost variations.

PEAK VS. OFF-PEAK

Both distance and topography factors exist during the peak and off-peak demand periods. Therefore, distinct cost functions will be developed for the two separate demand loads or periods. With respect to water supply, the off-peak demand is identified as average daily water consumption during the winter period. The assumption here is that for Cincinnati no sprinkling or

other peak-demands occur on an average winter day, such that off-peak demand could approach system capacity. An average winter day generally occurs between December 1 and March 31. Off-peak demand reflects the system's base load which consists of residential domestic demand and a normal commerical and industrial load.

Peak demand for any user, whether residential, commercial, or industrial, may occur at any moment. But, peak demand for the system usually exists at a specific time during the year. Peak system demand refers to that period of time in which the daily quantity demanded reaches a maximum for the year. This may happen more than once a year, but usually occurs during the late summer when most lawn sprinkling takes place. Peak system demand usually occurs between June 1 and September 30. Average daily demand during the system peak period is the dimension used to examine peak costs. The reason for this is two fold. First, very little storage is required to meet a peak day or a peak hour, but the peak week (or weeks) usually will strain the capacity of most water supply systems. Secondly, data on consumption is gathered either quarterly or monthly. As a result, average daily demand during the peak period is employed as an approximation to that of the peak week, which is not unrealistic since the system peak may last for more than one week.

COST FUNCTION: OFF-PEAK PERIOD

Two types of cost equations will be considered: peak and off-peak. Off-peak costs are related to the base load on the system or the average daily winter load only. Use of average daily annual load would overstate the magnitude of the off-peak load since peak use is included in the annual totals. The total cost of supplying the ith consumer in a water service zone k, can be estimated for the user's average daily load by adding together the relevant cost elements of A&T and T&D.

Although A&T costs consist of operating and capital components, average operating costs for the off-peak period will be considered constant for any single customer because no single customer is large enough to influence off-peak operating costs measurably and identifiably. Also, we shall treat average cost (AC) for A&T as a constant.

For capital expenditure or cost allocation, there is the problem of properly allocating costs between peak and off-peak periods. The capital facilities, though designed for the maximum day, is available during off-peak periods. Since, capital costs per unit of capacity vary depending upon the scale of the plant, and there exist economies of scale, it is difficult to evaluate off-peak capital costs for A&T. Therefore, the capital cost of A&T will be indirectly estimated for a hypothetical or simulated off-peak capacity plant to provide an estimate of the allocation of capacity cost to off-peak users. This estimation can be derived from equations developed in previous articles discussed in the literature review.

Once the total capital expenditure relevant for off-peak production is determined, the capital cost per unit of capacity may be allocated. This cost is also assumed constant per unit of acquired and treated water. Therefore, to allocate capacity costs, each consumer is treated identically and as a result is apportioned a fixed capacity cost per unit of output. This represents the proportion of capital expenditure or capacity required by the consumer to supply his off-peak demand.

DETAILED THEORETICAL COST FORMULATION

Overall principles of cost formulation for a water supply system have been discussed in this report. A basic tenet of the formulation is the division of costs into acquisition/treatment (A-T) costs at central plant

sites, and transmission/distribution (T-D) costs spread over the delivery system. A more detailed theoretical analysis of the cost formulation is presented in this Appendix.

DETAILED THEORETICAL FORMULATION

For A-T, capital cost or capacity cost may be considered a function of the planned volume of water to be supplied by the plant. The issue is not whether water will be supplied, but how much.

The relationship between annual capital cost, plant capacity and output volume can be formulated as follows:

$$CK^T = CK^T [K^T (V^T)] \qquad (24)$$

where,

CK^T = total capital cost of A-T per time period (depreciation);

K^T = capacity of the A-T plant; and

V^T = planned volume of output for the A-T plant.

The following equation signifies the dependence of CK^T on V^T. It is assumed that CK^T is continuously differentiable and that

$$\frac{\partial CK^T}{\partial V} = > 0 \text{ (marginal cost is positive)} \qquad (25)$$

$$\frac{\partial^2 CK^T}{\partial^2 V^2} = < 0 \text{ (economies of scale in capacity)} \qquad (26)$$

The last assumption appears reasonable in light of the numerous empirical estimates of central plant economies of scale.

A-T operating costs are strictly related to the quantity of water produced. Besides acquisition costs of raw water, operating costs include chemicals and labor.

The relationship between operating cost and water produced is shown below:

$$CO^T = CO^T (Q) \qquad (27)$$

where

CO^T = total operating cost of supplying a specific flow, and

Q = quantity of water treated and supplied per time period, or rate of output.

It is also assumed that CO^T is continuously differentiable and that

$$\frac{\partial CO^T}{\partial Q} = > 0 \tag{28}$$

$$\frac{\partial^2 CO^T}{\partial^2 Q^2} = > 0 \tag{29}$$

By combining equations 24 and 27, the total A-T cost, C^T, can be defined as:

$$C^T = CK^T[K^T(V^T)] + CO^T(Q) \tag{30}$$

This relation can be subdivided for peak and off-peak periods using the following manner:

$$TC^{1T} = w_1\ Q_1 K^T(K^T(K^T(V^T) + w_1 CO^T(Q) \tag{31}$$

$$TC^{2T} = (1 - w_1\ Q_1/K^T)CK^T(K^T(V^T)) + w_2 CO^T\ (Q) \tag{32}$$

where

Q_1 = off-peak output;

Q_2 = peak period output;

w_1 = proportion of the consumption cycle applicable to the off-peak period

w_2 = proportion of the consumption cycle applicable to the peak period;

$w_1 + w_2 = 1$;

TC^{1T} = total off-peak period A-T costs;

TC^{2T} = total peak period A-T costs; and

$C^T = TC^{1T} + TC^{2T}$

The structure of the equations (31) and (32) arise from the depreciation aspect of capital expense. It is evident that depreciation from the use of capital as an input in the production process occurs during the off-peak as

well as the peak periods. This situation exists whether a firm - or shifting - peak problem develops. The implications then is that some capital expense is incurred by off-peak use. Marginal capital cost, though, remains wholely attributable to the period.

TRANSMISSION-DISTRIBUTION

The costs of T-D are extremely complex because of the hydraulic engineering energy consumption relationships used in pumping water (see Volume I). Water transmission involves the major trunk lines that transport large volumes of water and the pumping stations necessary to move the water to the distribution system at the desired pressure. Distribution facilities convey the water from the trunk lines to the consumer. Water tanks or storage facilities are assumed part of the distribution system.

T-D capital expenditure is dependent upon the size or design capacity of pipelines, pumping stations, and storage facilities. Pipeline diameter can be used to relate capital cost to capacity, since the volume of water transmitted or distributed increases as diameter increases. Other factors, such as age and interior condition of the pipe impact replacement schedules.

The capacity of a pumping station is determined by the volume of pumped water it can handle during a given time period, as well as the number and sizes of pipes linked to the station. To increase capacity, a larger facility is required. For storage tanks, the capacity is dependent upon the total available volume. Storage is utilized mostly during peak-load periods.

The marginal capital cost of another unit of output is zero for pipelines and pumping stations up to the point of capacity. But, as mentioned before in the section on treatment plant capital cost, off-peak demand may be a significant factor in capital depreciation. Therefore, a proportional amount of capital cost is attributed to the off-peak load.

Storage tanks are used only when the pipelines and pumping stations have reached capacity. Therefore, the marginal cost of capital for storage tanks is zero until the system peak-load has been reached.

It is assumed in this analysis that storage tanks are erected for peak demand periods. As a result, the total storage cost can be allocated to the peak period even though tanks may be utilized during an off-peak period. The peak period is the period when the demand load for a selected service area of the total service area is greater than or equal to the combined capacity of the system pipes, pumping stations, and storage.

As mentioned previously operating costs of T-D, though centered on one main variable - energy - are very complex. A major portion of operating expenditures can be attributed to power consumption at pumping stations. Transportation of water over rough terrain and long distances requires a great amount of energy. Other operating costs, such as manpower and maintenance, are incurred, but are not as significant or as directly related to output as energy consumption.

The energy cost of pumping water depends upon the quantity of water supplied, the distance to a demand point, and the net altitude between the demand point and supply point. Other operating expenditures remain relatatively fixed with respect to output.

A water service zone is delineated by the average direction of water flow and the placement of pumping stations. Zonal capacity is dependent upon numerous elements, but it is assumed here that the dominant factors affecting capacity in a zone are capital components physically located within a zone. Numberous zones may exist in the areas of a water utility, however, all relationships refer to the sample zone.

Capital costs for a T-D zone are given by the following equations:

$$CK^D = CK^D[K^D(D(V))] \qquad (33)$$

$$CK^P = CK^P[K^P(V)] \tag{34}$$

$$CK^S = CK^S[K^S(V)] \tag{35}$$

where,

D = pipe diameter;

V = planned volume;

CK^D = total T-D pipe capital cost;

CK^P = total T-D pump station capital cost;

CK^S = total T-D storage cost;

K^D = T-D pipe capacity

K^S = T-D storage capacity; and

K^P = T-D pump station capacity.

It is assumed that the function CK^D, CK^P, and CK^S are continously differentiable as follows:

$$\frac{\partial CK^D}{\partial V} > 0 \tag{36}$$

$$\frac{\partial^2 CK^D}{\partial^2 V^2} = 0$$

$$\frac{\partial CK^P}{\partial V} > 0 \tag{38}$$

$$\frac{\partial CK^P}{\partial V^2} = 0 \tag{39}$$

$$\frac{\partial CK^S}{\partial V} > 0 \tag{40}$$

$$\frac{\partial^2 CK^S}{\partial^2 C^2} < 0$$

The assumptions about economies of scale are made either because of previous emprical work on the relation of capacity to capital cost or implicit knowledge of the type of facility considered.

Operating cost for the T-D component concentrates on energy use in pumping water. Total cost can be formulated as a function of distance, change in altitude, and flow. The equation incorporates a hydraulic engineering relationship as the basis for the cost equation. For ease of analysis, this complex function is reduced to a general relation, the properties of which are based on that equation as shown below:

$$CO^D = CO^D(Q,L,A) \tag{42}$$

where,

Q = flow;

A = change in altitude between the treatment plant and the service point;

L = pipe distance between the treatment plant and the service point; and

CO^D = total cost of energy consumption for pumping flow Q for a distance L with A change in altitude.

Equation 42 is assumed to have the following properties:

$$\frac{\partial CO^D}{\partial Q} > 0 \tag{43}$$

$$\frac{\partial CO^D}{\partial^2 Q^2} > 0 \tag{44}$$

$$\frac{\partial CO^D}{\partial L} > 0 \tag{45}$$

$$\frac{\partial^2 CO^D}{\partial L^2} > 0 \tag{46}$$

$$\frac{\partial^2 CO^D}{\partial^2 A^2} > 0 \tag{47}$$

$$\frac{\partial^2 CO^D}{\partial^2 A^2} > 0 \tag{48}$$

The second partial, with respect to Q is positive which signifies that for a given V, plant, and pipe system, as flow increases, energy cost rises at an increasing rate. This result shows the importance of separating the central plant from the transport system for evaluation of pricing and investment.

By combining equations 33, 34, 35 and 36, total T-D cost for a zone, C_D, is given by:

$$C^D = CK^D\,[K^D\,(D(V))] + CK^P\,[K^P(V)] + CK^S\,[K^S\,(V)] + CO^D\,[Q,L,A,)] \quad (49)$$

In the same manner as before, cost relations for peak and off-peak periods can be generated. Storage facilities, though, are primarily used during the peak period and in effect represent a different type of technology. Therefore, only pipe and pump capital elements appear in the off-peak cost function. These can be combined without loss of generality since the design of pump stations and pipes are interrelated. The peak period capacity cost will include storage. The off-peak and peak capacity costs are as follows.

$$CK^{1D} = CK^{PP}\,[K^{PD}\,(V)] \quad (50)$$

$$CD^{2D} = CK^{PD}\,[K^{PD}\,(V)] + CK^S\,[K^S\,(V)] \quad (51)$$

where

CK^{1D} = total T-D cost of off-peak capacity;

CK^{2D} = total T-D cost of peak period capacity, with storage;

V = planned output;

K^{PD} = pump and pipe capacity

By letting K^{PD} be the total pump and pipe capacity of the zone, capital cost can be apportioned in the same fashion as for A-T. Therefore, the total T-D capital and operating costs for peak and off-peak periods can be expressed as:

$$C^{1D} = (w_1 Q_1 / K^{PD})\,CK^{PD}\,[K^{PD}\,(V)] + w_1 CO^D\,(Q,L,A) \quad (52)$$

$$C^{2D} = (1 - w_1Q_1/K^{PD})\ CK^{PD}\ [K^{PD}\ (V)] + CK^{S}\ [K^{S}\ (V)] + w_2CO^{D}\ (Q,L,A) \quad (53)$$

where

CK^{PD} = cost of K^{PD};

Q_1 = off-peak flow;

Q_2 = peak flow;

C^{1D} = total of T-D off-peak cost; and

C^{2D} = total T-D peak cost.

To obtain total A-T and T-D cost functions for peak and off-peak periods, a combination of equations 32, 33, 53, and 54 must be made. Before integrating the A-T and T-D relations, the A-T equations must be slightly restructured to the zone level. The cost of supply through the A-T component is independent of T-D cost. A-T cost is the same regardless of zone. If capacity in the A-T section happened to be insufficient, T-D supply for all zones would be affected. Therefore, the A-T costs of one zone is a proportion of total A-T costs determined by the ratio of zonal flow to total flow.

This allocation can be represented as follows:

$$C^{1T} = (w_1Q_1/K)\ CK^{T}\ [K(V)] + w_1CO^{T}\ (Q) \quad (54)$$

$$C^{2T} = (1 - w_1Q_1/K)\ CK^{T}\ [K(V)] + w_2CO^{T}\ (Q) \quad (55)$$

where,

K = treatment capacity available for a zone;

C^{1T} = total A-T off-peak cost for a zone;

C^{2T} = total A-T peak cost for a zone;

CK^{T} = cost of K;

CO^{T} = A-T operating cost for a zone

C^{1} = total off-peak cost; and

C^{2} = total peak cost

Now by combining equations 54 and 55 with 52 and 53, the following zonal relationships for off-peak and peak A-T and T-D costs may be expressed:

$$C^1 = [w_1Q_1/K\ CL^T[K(V)] + w_1CO^T(Q) + (w_1Q_1/K)CK^{PD}[K(V)] + w_1CO^D(Q,L,A) \quad (56)$$

$$C^2 = (1-w_1Q_1/K)\ CK^T[K(V)] + w_2CO^T(Q) + CK^S[K^S(V)] + (1-w_1Q_1/K)\ CK^{PD}[K(V)] + w_2CO^D(Q,L,A) \quad (57)$$

Equations 56 and 57 together represent the total water supply capital and operating costs for a complete consumption cycle. These can be simplified to facilitate analysis. Since the CK^T and CK^{PD} functions have similar properties and levels of capital, the capital components of A-T and T-D can be combined. Storage capacity, K^S, though it must remain separate from non-storage capacity, is just an additon to system capacity. Therefore, incorporating these two adjustments into 56 and 57 provides:

$$C^1 = (w_1Q_1/K)\ CK[K(V)] + w_1CO^T(Q) + w_1CO^D(Q,L,A) \quad (58)$$

$$C^2 = (1-w_1Q_1/K)\ CK[K(V)] + CK^S[K(V)] + w_2CO^T(Q) + w_2CO^D(Q,L,A) \quad (59)$$

where,

$$CK[K(V)] = CK^T[K(V)] + CK^{PD}[K(V)]$$

For one zone, total capital and operating cost, TC, for the complete consumption cycle may be expressed as:

$$TC = C^1 + C^2 \quad (60)$$

This function represents the complexity of costs inherent in the A-T and T-D components as well as peak and off-peak for any zone of the system. These complexities are incorporated into the components of the Water Supply Simulation Model.

COST MINIMIZATION AND REGIONALIZATION

An obvious extension of the analysis discussed in the previous sections is to examine issues related to regionalization. There are many factors to be examinated associated with the establishment of regional systems.

Increasing quality requirements and associated increases in costs will no doubt also increase interest in the regional concept particularly among small systems. Figure 7 illustrates the cost issues associated with the regional concept.[57] The lower curve represents the original cost curve for the utility, and the higher curve illustrates the cost of water supply after new treatment is installed. In order to maintain a constant cost of supply an obvious tactic is to increase the amount of water supplied. The most effective way to increase supply and drive down cost would therefore be to move toward a regional system. It is obvious that increased costs whether they are associated with regulations or not will tend to force consideration of regionalization.

The AWWA committee on regionalization has listed a number of benefits and problems associated with regionalization. These items are detailed in the following sections.[58]

BENEFITS FROM REGIONALIZATION

Regionalization will facilitate improved and unified management of water systems by providing for more comprehensive supervision and better day-to-day direction of operations. According to the AWWA committee regionalization will enhance:

1. Operation and Maintenance - Regionalization will provide for more comprehensive supervision and day-to-day management.

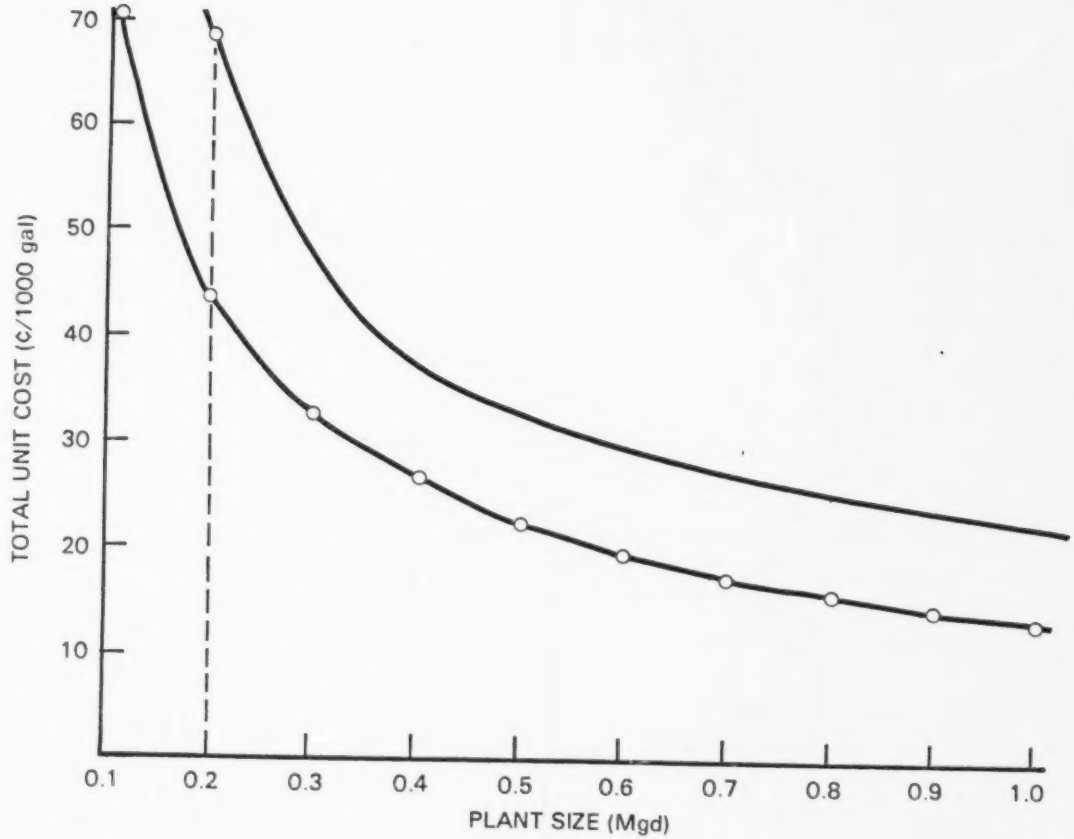


Figure 7. Total unit treatment cost for package systems.

2. Planning and Design - Regionalization will allow for optimium planning of the water supply system particularly where the original individual systems are interconnected or could be readily interconnected.

3. Financing - A more uniform rate base and better financing because the cost of service will be distributed over a larger geographical area.

4. Government - Regionalization will assist the state regulatory agencies by reducing the number of management organizations needed to monitor water quality.

PROBLEMS WITH REGIONALIZATION

According to the AWWA Committee the problems associated with regionalization fall into the following catagories:

1. Public Attitude and Government - A community may be opposed to loss of control of its water system income which may be divereted to a regional general fund.

2. Inequities and Financing - some participating municipalites may be concerned about loss of water sales revenue used for other general purpose needs.

Dan Okun, one of the outspoken advocates for regionalization has studied the regionalization process in England and Wales.[59] According to Okun, England and Wales now have the most efficient program of water managment in the world. In the English model regional water authorities are responsible for the planning construction management, operation, and financing for all water based activities for 50 million people in England and Wales. Okun feels that this model could be adapted in the United States at the State

level and cites several examples in which States have taken the lead in providing the mechanism for establishing regional water supplies.

One possible barrier to development of regional water systems in the U.S. is that historically, treated water has been provided by municipal governments. Clemens suggested the following reasons for this arrangement.[60]

1. Water treatment and supply is a relatively simple operation that can easily be carried out on a small scale.
2. Over the years, few changes have occurred in water treatment technology to make the process more difficult or expensive to provide on a local level.
3. Treated water can be supplied by municipalities as a joint service with fire protection.
4. Treated water supply involves the public health, and as such it is generally viewed as the function of government.
5. Significant scale economies are lacking at the local level.
6. The private sector has failed to enter the market in many cases.

The Safe Drinking Water Act, along with other environmental legislation, encourages the development of regional systems for managing water supplies. Regionalization has great appeal to regulatory groups because it reduces the number of individual entities with which they must work.[61] Small systems tend to have more quality control problems than do large systems. Quality control problems can often be solved effectively in a regional context. Another possibility involves the centralization of purchasing maintenance, and various management support items. A common argument is that regional systems hydraulically interconnected exhibit economies of scale, thereby minimizing costs to the consumer. The following section examines some of these issues in more detail.

HYDRAULICALLY INTERCONNECTED SYSTEMS

The economies of scale argument holds for a limited set of circumstances, as can be demonstrated by the following data. Figure 8 shows unit costs of water treatment uncorrected for inflation for the Fairfax County Water Authority (Virginia) and for four other utilities over a 10-year period.

The Fairfax County Water Authority was developed by acquiring individual water service areas around the original Alexandra Water Company and, as such, has become a regional water supply utility.[62] As the Fairfax utility has grown the unit costs have decreased. These data support an economies of scale argument. Compared to the other stable utilities, the unit costs for the Fairfax Authority continuously declined between years 1 and 5, the periods of maximum growth.

On the other hand, research indicates that limitations to the economies of scale associated with regionalization may exist. The following section deals with an analytic attempt to analyze the cost trade-off between a central plant and decentralized transmission components of a utility.[63]

ECONOMICS OF REGIONALIZATION

In order to completely understand the costs associated with water supply, it is important to be able to properly analyze the variuous cost functions that make up the water supply system. Physically, it is possible to separate the water supply system into three components. The first is the treatment plant, the second is the transmission and distribution system, and the third is management or support services.[64] Each of these components has a different cost function. The unit costs associated with treatment facilities are usually assumed to decrease as the quantity of service increases. The transmission and distribution system (the transportation costs of water) are more directly affected by the characteristics

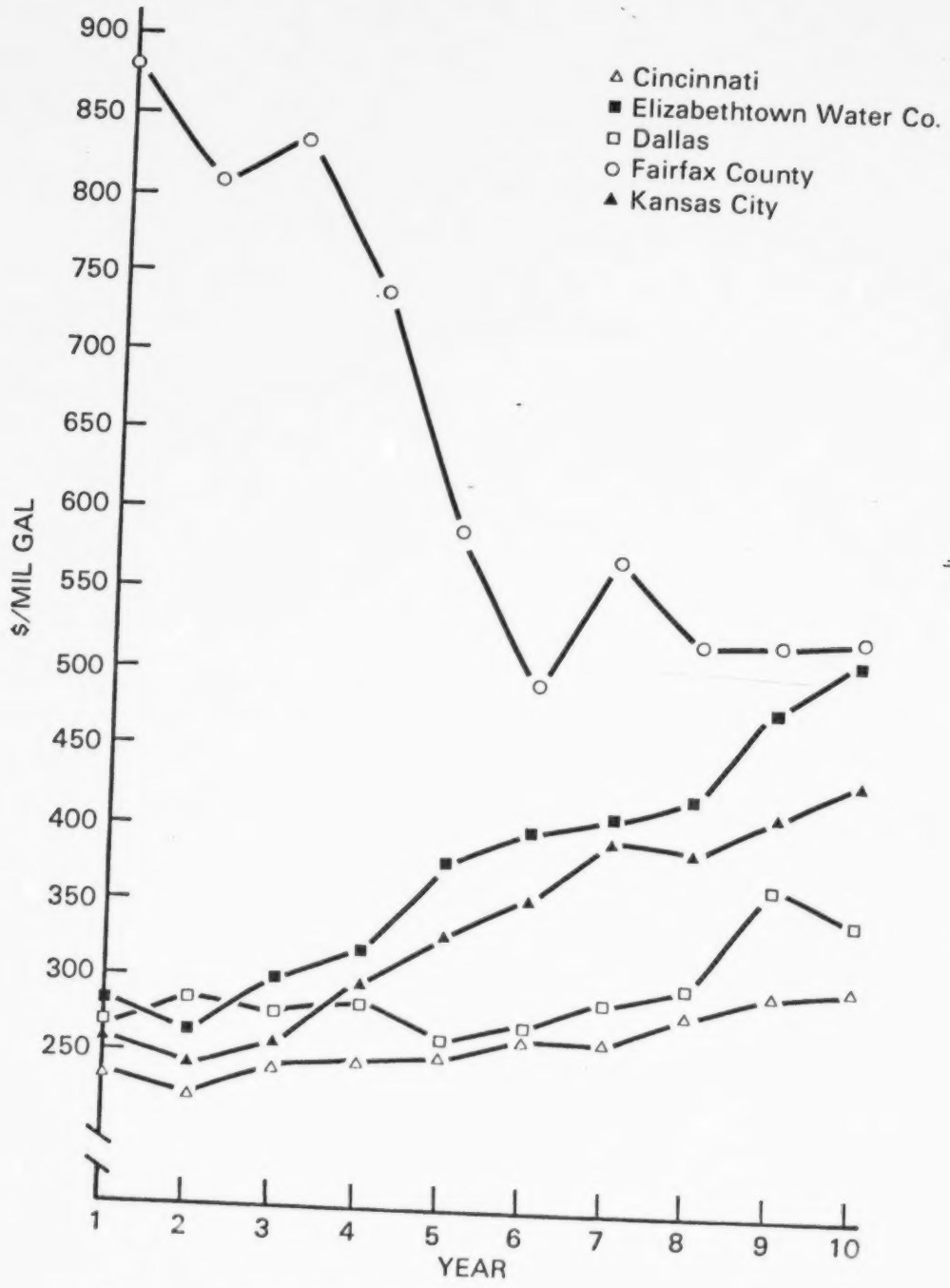


Figure 8. Total unit cost for five utilities

of the area being served. As pointed out be Dajani and Gemmell, "Economies of scale may be offset by diseconomies of dispersion, agglomeration or spatial arrangement, ...".[64]

A simple argument confirms the reasonableness of the above statement. As previously defined, economies of scale imply decreasing marginal costs with increasing values of the variable in question, or more specifically in the model $C = a\ Q^b$, as long as $b<1$ economies of scale exist (there are incentives to overbuilding). Analysis has found that not all cost centers exhibit economies of scale (Table 1), especially acquisition.[62]

Also support services (overhead) show low economies of scale, results that make the neglect of overhead costs in the regionalization planning problem reasonable. Treatment costs definitely present high economies of scale, a fact confirmed by several investigators.[65,66,67] However, transmission and distribution again have low economies of scale based on the flow component in Table 1. The above results could lead to the conclusion that economies of scale are concentrated in treatment plants. This is partially true, but the results are distorted by considering only flow as the factor affecting costs.

Some insight can be gained by the following analysis: consider that a pipeline conveys water between two sections, at a rate of Q, m^3/s. Assuming that the head loss is the extension L of this pipeline is H, the diameter is given by:

$$D = k\ Q^{.38}\ \left(\frac{L}{H}\right)^{0.205} \quad \text{(Hazen-Williams formula)} \tag{61}$$

Capital costs of pipelines are expressed by:

$$C_m = 2.16\ D^{1.2} \tag{62}$$

where

C_m = construction cost in dollars per mile

D = pipe diameter, inches

TABLE 1

OPERATING AND MAINTENANCE AND CAPITAL COSTS FOR ALL UTILITIES

Item	Operating Cost $C = aQ^b e^{st}$				Capital Cost[8] $C = cO^b e^{st}$			
(1)	a (2)	b (3)	s (4)	r^2 (5)	a (6)	b (7)	s (8)	r^2 (9)
Acquisition	1.4	1.23	0.043	0.64	$2x10^{-3}$	2.94	0.000	0.67
Treatment	2,379.1	0.52	0.063	0.56	32.8	0.82	0.066	0.40
Transmission & Distribution	211.0	0.82	0.052	0.92	178.0	0.89	0.036	0.86
Support Services	78.43	0.95	0.073	0.95	24.35	0.88	0.044	0.66
Total	360.4	0.91	0.056	0.93	193.8	0.91	0.043	0.86

*Capital cost in this case is reported as annual depreciation in dollars/yr.

NOTE: t = relative time, starting with year 1 as the first year of data (1965):
Q = revenue-producing water in millions of gallons per year:
C = annual cost in dollars per year.

The total construction cost of the pipeline with length L is:

$$C = 2.16\ LD^{1.2} \tag{63}$$

and using the above expression for D

$$C = KQ^{0.46}\ \frac{L^{1.25}}{H^{0.25}} \tag{64}$$

where K is a constant. It is very clear from the above expression that strong economies of scale exist in the Q component and disconomies exist in the L component. For a utility which is expanding (increasing L) at a rate faster then it is increasing pumpage (increasing Q) transmission-distribution costs will exhibit diseconomies of scale. In a utility in which over capacity exists (increasing Q, relative to L) the transmission-distribution system will exhibit economies of scale.

Assume now that a pumping station is necessary to convey water in the pipeline. The energy spent in a given period in this pumping station can be expressed by:

$$E = \beta\ Q\ H \tag{65}$$

where

β = constant for the case

$H = H_G + H_L$, with H_G the hydrostatic head and H_L the head loss. The head loss can be expressed by (Hazen and Williams):

$$H_L = \frac{Q^{1.85}}{D^{4.87}}\ L \tag{66}$$

and the energy:

$$E = \beta Q(H_G + \frac{Q^{1.85}}{D^{4.87}}L) \tag{67}$$

assuming that costs of energy are given by a linear relation:

$$C_E = aE \tag{68}$$

the opposing cost component given by energy is

$$C_E = a\beta QH_G + \frac{a\beta Q^{2.85}L}{H^{4.87}} \tag{69}$$

Based on equation (69) no economies of scale exist on either Q or L. Equation (69) shows the inevitable loss of economies of scale beyond a certain system size.

The logical consequence of this analysis is to develop a model to analyze for the most efficient system size. Development of such a model is discussed in the following section.

TOTAL COST MODEL

Logic developed in the previous section indicates that if a total cost model is developed it should consist of two component parts: Acquisition -

Treatment; and Transmission-Distribution. Therefore, a total cost function could be formulated as follows:

$$C_{TOT} = C_T + C_D \tag{70}$$

where

C_{TOT} = annual cost for water supply in mil dollars/yr

C_T = annual cost for water treatment in mil dollars/yr

C_D = annual cost for transmission and distribution in mil dollars/yr

Equation 70 is formulated somewhat differently than those previosuly discussed. It combines the total annual cost of each component to get total annual cost for the system, but maintains the separability of the two relationships. The first term represents the cost of treatment and the second term the distribution cost. Normally C_T and C_D are considered to be a function of the water produced, Q.

QUANTITY, DISTANCE, AND POPULATION DENSITY

In this model it is assumed that the service is produced or made available at a single location. For simplicity, we have taken a circular urban area of radius r. Demand per unit area or density is assumed to be a bounded nonnegative function Q (r), of the distance from the center of the area, r. The assumptions of circularity and radial symmetry of demand simplify the analysis of implying that all transmission of services is stricly outward from the center of the area and that lateral flows are never necessary. Demand may be calculated for a given area at a given point in the service by multiplying population density by service area and service demand per capita. This relationship may be expressed as follows:

$$Q = CP_DA \tag{71}$$

where

Q = total water use for a given area per year;

C = per capita use per year;

P_D = population density;

A = the area over which useage is to be determined.

Several studies have provided strong evidence that population density falls off fairly smoothly and at a decreasing rate as one moves away from the city center.[68] These studies have shown that the negative exponential function provides a good approximation to these decreasing popluation densities. It can be written:

$$P_D = Ke^{-\lambda r} \tag{72}$$

where P_D is the density r miles from the center, e is the base of the natural logarithm, and K and λ are parameters to be estimated from the data. K is the measure of density at the city center, and λ, which is positive, is a measure of the rate at which density declines with distance. If λ is large, then it follows that the density falls off rapidly; if it is small, density falls off slowly.

By substituting equation (72) into equation (71) and integrating over the service area assuming a flat idealized plain, it is possible to find a deterministic relationship between Q and d, as shown below:

$$Q = CK \int_0^{2\pi} \int_0^{d} e^{-\lambda r} r \, dr \, d\Theta \tag{73}$$

$$= \frac{2\pi CK}{\lambda^2} [1-e^{-\lambda d}(1+\lambda d)] \tag{74}$$

where

d = limit of integration as the distance from the central reference point of the service area.

In equation 74, if d = o, then Q = o and if d $\to \infty$, then Q = $\frac{2\pi CCK}{\lambda^2}$. Q increases with d as shown in the relationship above, and equation (74) demonstrates the link between water produced (Q), per capita consumption (C), initial population density (K), density gradient (λ) and distance (d).

ESTIMATING EQUATION PARAMETERS

To use equation 74, it is necessary to estimate the parameters. Data utilized to estimate these parameters have been taken from studies conducted by the U.S. Environmental Protection Agency.[69] The data used to estimate the treatment-acquisition component resulted from a two-year study of 12 selected utilities. Data were collected for 10 years from at least one class A utility (revenues greater than $500,000/yr) in each of EPA's 10 regions. Because most of the utilities were large the parameters will reflect this bias. The finished water from all of the utilities selected met the 1962 Public Health Service Drinking Water Standards. The estimated equation for the acquisition-treatment function is:[69,70]

$$C_T = 513Q^{0.77} \qquad (R^2 = 0.61) \qquad (75)$$

where

C_T = total cost of acquisition and treatment, mil $/yr; and

Q = revenue-producing water in million gallons per year.

In general

$$C_T = DQ^{\alpha} \qquad (76)$$

As can be seen from equation 75 the rate of increase of cost with respect to water produced is less than one. Therefore the unit cost of treatment (C_T/Q) will decrease with increasing Q. In other words the treatment-acquisition term in equation (70) has unlimited economies of scale. It is this concept that has encouraged designers, planner and regulators to assume that

regional system are universally cost effective. The treatment-acquisition term is the easiest relationship to obtain and the easiest to understand by most individuals traditionally involved in water utility decision making.

Estimation of the transmission-distribution function is rather complex as compared to equation (75). Facilities associated with equation 75 are limited and therefore in general cost records are easy to obtain. In contrast, obtaining the data associated with the transmission-distribution function is difficult to obtain and interpert. Using data from the pipe network of one water utility, estimation of the transmission-distribution cost equation was made. This analysis involved calculating the cost associated with a 1000 different nodes in the transmission-distribution network. The following equation resulted:

$$C_{DP} = 408\ Q_p^{.82} \qquad (R^2 = 0.84) \qquad (77)$$

where

C_{DP} = total cost of transmission-distribution for Q at a point in the water utility service area.

Q_P = the revenue-producing water at a point in the service area.

In general

$$C_{DP} = BQ_P^{\beta} \qquad (78)$$

Equation 78 does not correspond exactly to the transmission-distribution component of equation 70. Equation 78 represents the total cost of supplying quantity Q_P to a point of consumption in the service area. Therefore, equation 78 must be integrated over the distance and area served as shown below:

$$C_D = \int_o^{\overline{\Theta}} \int_o^{d} C_{DP}\ r\ dr\ d\Theta \qquad (79)$$

where

C_D = total of transmission-distribution for Q over the entire water utility service area.

$\overline{\Theta}$ = limit of integration for service area geometry.

The angle of integration Θ is an important variable in the final set of equations. In the earlier discussion it was assumed that the service area was a flat idealized plain, and equation 73 was developed. In fact the service area may be highly irregular and by assuming different values of Θ, this irregularity can be approximated. An example illustrating this idea is discussed later. From equation 71, the total water use for a point is:

$$Q_p = CP_D = CKe^{-\lambda r} \tag{80}$$

where

Q_p = water use at a point in the service area, mil gal/yr;

and

r = distance from the treatment plant in miles.

Substituting equation 80 into 79 and performing the integration step yields

$$C_D = \frac{\overline{\Theta}B\,(CK)^{\beta}}{\beta^2\,\lambda^2}\,[1-e^{-\beta\lambda d}\,(1+\beta\lambda d] \tag{81}$$

Substituting equation 81 into the second term on the right hand side of equation 69 and equation 73 into equation 74 and then the first term of equation 69 yields:

$$C_{TOT} = A\left[\frac{\overline{\Theta}CK}{\lambda^2}\,[1-e^{-\lambda d}\,(1+\lambda d]^{\alpha}\right]$$

$$+\,\frac{\overline{\Theta}B\,(CK)^{\beta}}{\beta^2\,\lambda^2}\,[1-e^{-\beta\lambda d}\,(1+\beta\lambda d)] \tag{82}$$

To find the total unit cost function (TUC), divide equation 82 by equation 73 to get

$$TUC = A \left[\overline{C\Theta K} \frac{[1-e^{-\lambda d}(1+\lambda d)]}{\lambda^2} \right]^{\alpha-1} + \left[\frac{[B(CK)^{\beta-1}]^{2}/\beta \; [1-e^{-\beta\lambda d}(1+\beta\lambda d)]}{[1-e^{-\lambda d}(1+\lambda d)]} \right] \quad (83)$$

Taking the partial derivative of equation 88 with respect to d yields:

$$\frac{\partial TUC}{\partial d} = A(\alpha-1)\left[\frac{\overline{\Theta}CK}{\lambda^2}[1-e^{-\lambda d}(1-\lambda d)] \right]^{\alpha-2} [\overline{\Theta} dCK^{-\lambda d}]$$

$$- \frac{B(CK)^{\beta-1}}{\beta^2}[1-e^{-\beta\lambda d})(1+\beta\lambda d)][1-e^{-\lambda d}(1+\lambda d)]^{-2}[\lambda d e^{2-\lambda d}]$$

$$+ \frac{B(CK)^{\beta-1}}{\beta^2}[1-e^{-\lambda d}(1+\lambda d)]^{-1}[\beta^2 \lambda^2 d e^{-\beta\lambda d}] \quad (84)$$

Equation 84 indicates the effect on unit costs of a marginal change in distance. Using the estimated values for A, B, α and β from equations 74 and 76 and appropriate values for λ, C and K equation 84 can be solved for the minimum cost distance by setting it equal to 0.

ANALYSIS AND RESULTS

The approach presented here can be used to study various policy and planning alternatives. An item of interest to most water supply professionals is the relationship between system expansion, increasing per capita demand

for water and unit cost for water supply. Still another important consideration is the least-cost size for a utility. These issues are explored via the use of the mathematical model in the following sections.

SYSTEM GROWTH SCENARIOS

Using equations 83 and 84, costs for a selected midwestern water utility were examined to verify the models capability to simulate the cost characteristics of an operating water utility. Table 2 shows the parameter values assumed for the utility, the actual budget values, and the estimated total treatment acquisition and transmission-distribution cost for the utility. The flexibility of this model is evident here in that it will handle most circular service areas, but not all utility service areas possess such a shape. However, the equation can easily be adjusted to conform to noncircular service areas, such as a simicircle or pie slice. This can be done by adjusting the 2π limit of integration to a more appropriate value. In fact, for the selected water utility, the limit of integration actually corresponds closer to 0.4π instead of 2π. Using this new limit of integration Q and cost can be more accurately estimated. As can be seen, equations 83 and 84 yield fairly close estimates of the total annual costs for the critical components.[71]

TABLE 2

BUDGETARY CALCULATIONS

C (mil gal/ capita/yr)	K	λ	Q (mil gal yr)	Estimated Treatment-Acquistion Cost	Estimated Treatment Distribution Cost	Acutal Treatment Acquistion Cost	Actual Treatment Distribution Cost
0.054750	15,000	.12	49,600	2,116,597	7,605,031	2,009,977	6,446,962

As a further illustration of the use of equations 83 and 84 a growth scenario was assumed for 10 years for a hypothetical utility (Table 3). The growth scenario over the 10-year period is illustrated by declining values of λ (column 2), increasing per capita consumption (column 4), expansion of the service area (column 3), and increasing total Q (column 5). Columns 6 and 7 are hypothetical component costs. As can be seen from column 10, the total unit cost (in real dollars) is declining over time as has been observed in many actual utility studies. This analysis provides a futher verification of the model's unsefulness and validity.

TABLE 3

GROWTH SCENARIO

Year	λ	d (miles)	C (mil gal capital/ yr)	Q (mil gal/ yr)	Total A-T Cost ($/yr)	Total A-T Cost ($/yr)	Unit A-T Cost ($/yr)	Unit A-T Cost ($/yr)	TUC ($/mil gal)
1	.3	7.0	.018250	11,856	703,153	2,169,356	59.31	182.98	242.29
2	.3	7.2	.027385	18,220	978,903	3,113,303	53.73	170.87	224.66
3	.3	7.4	.036500	24,855	1,243,329	4,050,959	50.02	162.98	213.00
4	.2	7.6	.040150	42,461	1,877,889	6,424,109	44.23	151.29	195.52
5	.2	7.8	.043800	47,684	2,053,356	7,127,497	43.06	149.47	192.53
6	.2	8.6	.047450	53,113	2,231,115	7,853,036	42.01	147.86	189.87
7	.1	8.2	.051100	95,557	3,506,869	12,936,492	36.70	135.38	172.08
8	.1	8.4	.054750	106,118	3,801,674	14,218,365	35.82	133.99	169.81
9	.1	8.6	.058400	117,192	4,103,636	15,552,887	35.02	132.71	167.70
10	.1	8.8	.062050	128,779	4,412,635	16,940,008	34.25	131.54	165.80

Equations 83 and 84 also yield some additional insight as to how utility costs may behave if as in many utility service areas per capita consumption per unit area begins to decline with distance. As can be easily seen declining consumption per unit area will force unit costs to rise. If at some point inflation causes A, B, in equation 83 to increase to some level such that real price rises and C begins to decrease, then unit costs will also increase. Equation 80 and 84 therefore provide a concise and powerful mechanism to evaluate and simulate both the affects of inflation, changes in spatial and demographic data and policy decisions over space and time.

EFFICENT UTILITY SIZE

A concept that plagues most utility managers is the most efficient size for a utility service area. Electrical utilities tend to over invest in utility facilities due to limiations on rate of return. With a fixed rate of return the only way an electrical utility can generate additional funds is to invest in more capital for facilities which may result in a utility service area greater than the most efficient size. Water utility managers tend to assume unlimited economies of scale for water treatment and delivery systems. This often lead to water utilities that have service areas that are larger than the most efficient size. Equations 80 and 84 can be used to study some of the implications of efficient service area size and configurations. In the following example a perfectly circular area of service is assumed and the minimum cost distance from the treatment facility is assumed as a surrogate for system size.

By substituting appropriate values for the parameters into equations 83 and 84, the effects of distance on unit costs can be studied. Table 4 demonstrates the effects of changing the parameter values in equation 84. For example, lines 1 through 4 illustrate the effect of decreasing λ,

holding C and K constant. As can be seen, d (the minimum cost distance ie., $\frac{\partial TUC}{\partial d} = 0$) increases dramatically with decreasing λ. Larger values of λ are associated with systems serving area with population densities that fall rapidly as one approaches the suburbs. Most metropolitan areas are experiencing a transition from high but rapidly declining densities to lower but more uniform population densities.

Lines 1 through 4 also show the relationship between λ, population density and the minimum cost distance. The relationship is given by equation 84. For each set of K, λ, the popultion densities at the minimum "optimal" distance are 4050; 4500; 5250; and 6300 respectively. Therefore as population densities decrease the least-cost distance for utility size increases.

TABLE 4

EFFECT OF PARAMETER LEVELS ON MINIMUM COST DISTANCE

λ	C (mil gal/capita/yr	K (people/sq mi)	d (miles)
0.4	.054750	15,000	3.3
0.3	.054750	15,000	4.0
0.2	.054750	15,000	5.3
0.1	.054750	15,000	8.7
0.2	.018250	15,000	5.5
0.2	.036500	15,000	5.4
0.2	.054750	15,000	5.3
0.2	.073000	15,000	5.3
0.2	.054750	5,000	5.5
0.2	.054750	10,000	5.4
0.2	.054750	15,000	5.3
0.2	.054750	20,000	5.3

Lines 5 through 12 clearly illustrate that holding λ constant and changing C and K has little effect on the minimum cost d. Data in Table 4 shows that the most important variable determining "optimal" or least-cost system size as measured by the minimum cost distance is population distribution rather than the abolute values of population or per capita consumption.

Using the coefficeint estimated for equation 80 and 82, and selecting parameters for C, K, and λ selected for this utility were C = .054750; K = 15,000; and λ = 0.12. Using these values total unit costs were calculated from equation 83, for various distances from the treatment plant. Equation 74 was used to estimate the change in Q with d. These calculations are summarized in Table 5. Equation 84 was used to estimate marginal costs.

Figure 9 illustrates the unit and marginal cost relationships with distance. The unit or average cost curve represents the unit cost for supplying the whole output to a service area of a given size. As distance from the treatment plant rises, or the service area expands, the incremental costs can be determined from the marginal cost curve. The marginal costs reflect the change in total costs from increased output as the service area expands, given a population density distribution. It can be easily seen from Table 5 that the minimum cost point for this utility is approximately 8.3 miles from the treatment plant.

TABLE 5

SAMPLE CALCULATIONS FOR DISTANCE COST RELATIONSHIPS*

Q (mil gal/yr)	d (mile)	Treatment Unit Cost ($/mil gal)	Transmission Unit Cost ($/mil gal)	Total Unit Cost ($/mil gal)	Marginal Cost ($/mil gal)
8808.47	2	63.50	125.45	188.95	188.95
30172.25	4	47.84	128.91	176.75	171.72
58332.44	6	41.11	132.31	173.42	169.80
89416.04	8	37.26	135.64	172.90	171.94
120893.44	10	34.77	138.89	173.66	175.80
151181.43	12	33.02	142.05	175.07	180.71
179354.48	14	31.75	145.10	176.85	186.30
204936.20	16	30.79	148.03	178.82	192.64
227749.76	18	30.05	150.83	180.88	199.42
247811.79	20	29.48	153.50	182.98	206.88

*Assumptions: $C = .054750$

$\lambda = .12$

$K = 15,000$

Table 6 is similar to Table 5, but for a utility with an assumed output based upon $C = .018250$. Figure 10 presents the relevant marginal and average cost relationships. The minimum cost distance for this situlation appears to be about 8.5 miles. The relationship shown in Table 4, namely, that as output goes down the minimum cost distance rises, is born out here. This may be explained by the fact that the utility with the lower output is still

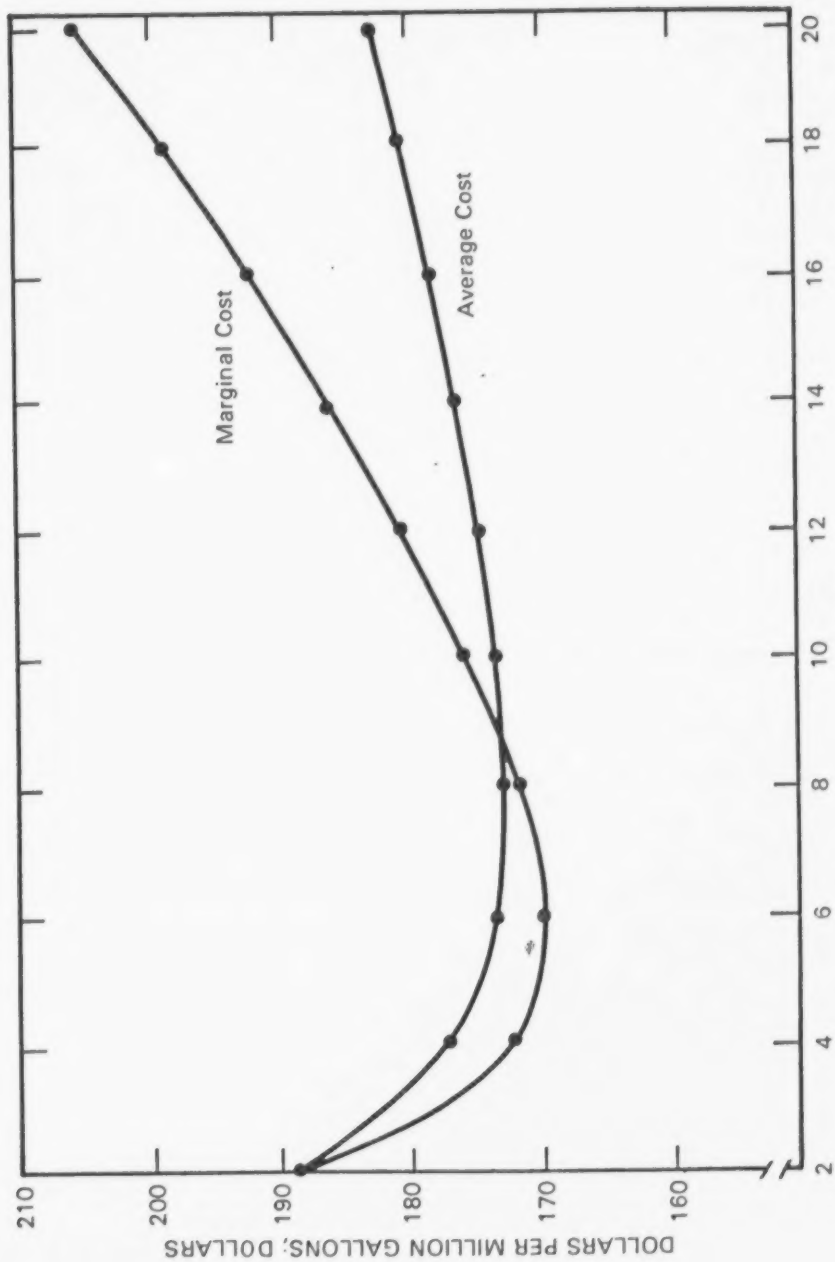


Figure 9. Unit and marginal cost with distance using 150 gal/cap/day.

obtaining returns to scale from the treatment component which continues to offset the transmission diseconomies. However, this effect only adds one to two-thirds of a mile to the minimum cost distance. It is also obvious that the smaller utility has a significantly higher unit cost over the entire range of distances.

TABLE 6

SAMPLE CALCULATIONS FOR DISTANCE COST RELATIONSHIPS

Q (mil gal/yr)	d (mile)	Treatment Unit Cost ($/mil gal)	Transmission Unit Cost ($/mil gal)	Total Unit Cost ($/mil gal)	Marginal Cost ($/mil gal)
2936.16	2	81.76	152.88	234.64	234.64
10057.44	4	61.59	157.10	218.69	212.11
19444.19	6	52.93	161.24	214.17	209.33
29805.42	8	47.98	165.30	213.48	211.61
40297.91	10	44.76	169.26	214.02	216.14
50393.93	12	42.52	173.11	215.63	222.62
59782.85	14	40.88	176.83	217.71	228.89
68312.23	16	39.64	180.39	220.03	236.37
75916.77	18	38.69	183.81	222.50	244.64
82604.12	20	37.95	187.06	225.01	253.45

*Assumptions: $C = .018250$

$\lambda = .12$

$K = 15{,}000$

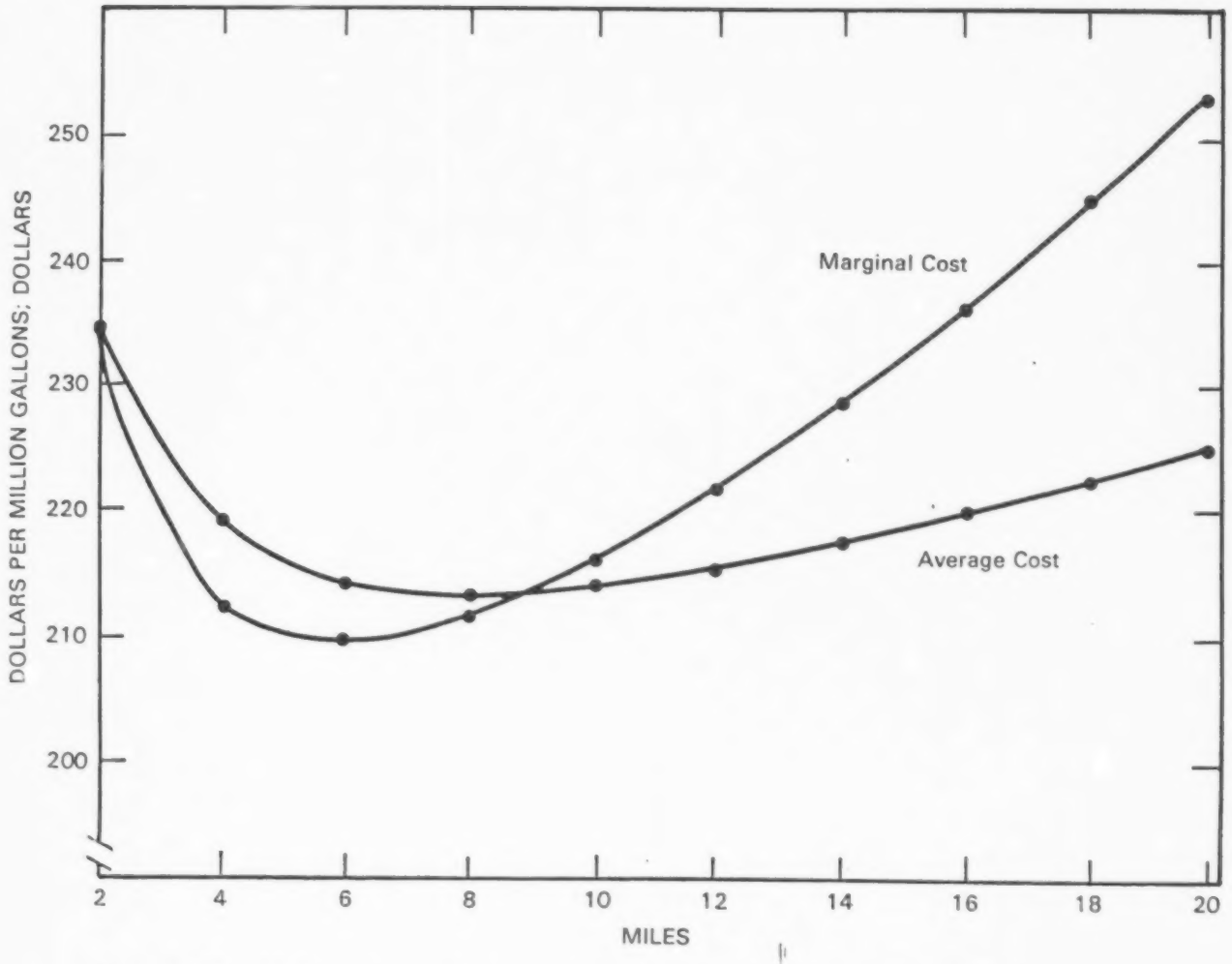


Figure 10. Unit and marginal cost with distance using 50 gal/cap/day.

These calculations illustrate that there may exist a maximum efficient size for a water utility. Utility managers and planners should therefore give careful thought to plans for expansion and to the proper pricing mechanisms to be applied to situations similar to those described in Figures 9 and 10. Figures 9 and 10 clearly show that up to the minimum cost distance each customer reduces average and marginal cost but beyond that point costs rise continually and the utility is justified in charging more for the customer further from the treatment plant.

ALTERNATIVE SERVICE FOR OUTLYING AREA

The curves shown in Figures 9 and 10 can be used to illustrate the trade-offs that are involved in making decisions regarding the opportunity cost for a large central utility to service outlying areas. Average and marginal cost curves in Figure 9 can be assumed to be representative of the large central facility. The cost curves in Figure 10 are more representative of a small utility. For purposes of this analysis assume that the large utility serves the area represented on the horizontal axis in Figure 11 by the distance 0-20. Let us assume that an outlying community has the option of building its own water utility to serve the area represented by the distance 20-40, or of being served by the central utility. According to the cost curves plotted in Figure 11, using an average cost basis would lead decision makers to select service from the central facility. This approach (average cost) is the one most often used by municipal decision makers. However the marginal cost curves lead to a completely different solution. According to the marginal cost curves the minimum cost solution would lead to the central utility stopping its service area at slightly over 24 miles. The small community would build its own utility and serve the area from 24 to 40 miles.

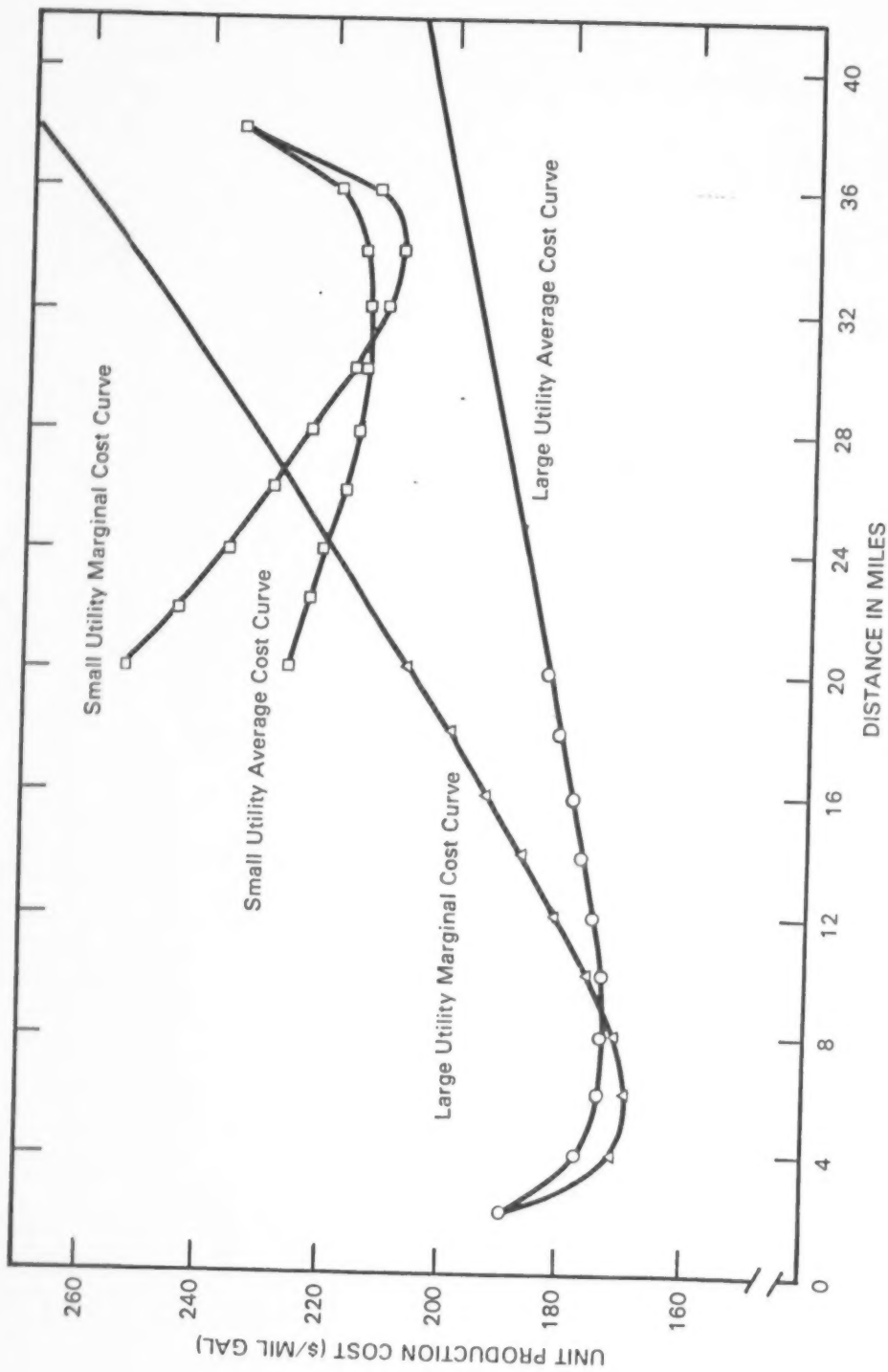


Figure 11. Cost curves for large and small utilities

Such utilities may in fact be more efficient then disaggregrated utilities. However, this analysis has shown that there may be limits to the regionalization concept. Regulatory agencies may mistakenly recommed regional systems to minimize their own effort while actually causing inefficiences in water supply management.

It is recommeded therefore that managers and planners of utilities who may feel the pressure of regulatory bodies to develop regional system, perform careful analysis before commiting to such a course of action. Hopefully, the data analysis presented in this paper will assist in making such analysis.

SPATIAL COSTING METHODOLOGY

The analysis to this point strongly suggests there are definite limits to the efficient size of a utility. Given the diseconomies of increasing distribution network size and the economies of scale associated with treatment there is some minimum cost system size. Because of shifting parameter characteristics in equation 83 and because of data collection limitations it is very difficult to define these cost efficiency limitations with any degree of precision. In order to provide an operational tool which can be used by individual utilities to find its most efficient size, EPA's Drinking Water Research Division had developed a spatial cost analysis system.[72]

Figure 12 is a simplified schematic of a typical water utility with a reservoir raw water source, illustrating the concept of dividing the water utility into the functions of acquisition, treatment, and delivery. This technique can be adapted to all water utility systems regardless of their physical structure. Use of this concept allows identification of costs not only to the specific functions of acquisition, treatment, or delivery but

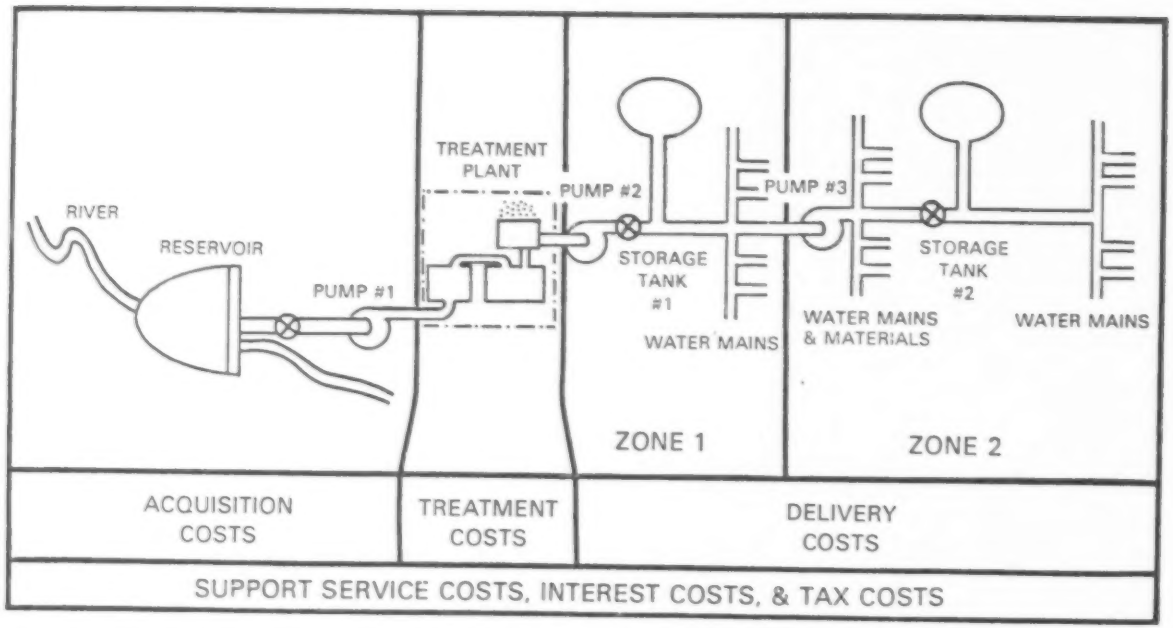


Figure 12. Water utility simplified schematic.

also to the subfunction level. For example, using Figure 12, subfunctions of acquisition include source of supply, reservoir, pumps, and transmission lines. Subfunctions of delivery include pumps, storage tanks, transmission, and distribution.

Based on this system of cost analysis, the cost of water is identified at various locations in the utility system, and as the water moves from its source to its destination, costs are transferred from the cost centers to the water. For example, as shown in Figure 12, the acquisition cost consists of all costs incurred to move water to the treatment plant. When the water enters the treatment plant, the cost of treating the water is added to the acquistion cost. Cost also is incurred by additional pumping, located within the treatment plant, to move the water into the delivery area. However, this is considered a subfunction of delivery. In addition, costs such as transmission and distribution are accumulated in each zone. The transmission costs are those for moving water to zone 1 and zone 2. The transmission costs include the network of mains and laterals that deliver water to customers in zones 1 and 2. Analysis of the system in Figure 12 reveals that an element of the pumping cost for pump No. 2 is incurred to move water through zone 1 to zone 2, and another cost element is incurred in delivering water through the laterals to customers in zone 1. Similarly, the transmission mains include both a transmission cost element and a delivery cost element. Storage costs are assigned only to the zone in which the storage facility is located because no element of this cost is applied to any other zone.

Two types of costs were identified as this technique was refined. One type was associated directly with the operating functions of acquistion, treatment, and delivery; and the other type could not be identified with any

specific operating function. These non-operating costs include billing, accounting, management, etc., and were placed in a separate category called support services. Figure 12 shows these across the utility operation.

Within this general concept, two basic types of information are required, as shown by the matrix in Figure 13. These types of information match the physical system depicted in Figure 12. Across the top of the matrix are listed the following specific utility functions: acquistion, treatment, delivery, and support services. Down the side of the matrix all costs of operating the utility (labor, power, etc.) are entered. These cost categories can be cross-referenced againt the utility where appropriate. Documentation of costs in this format makes it possible to retrieve and display the various levels or types of information desired. For example, the cost of labor for treating water can be determined by examining the first cost category listed within the treatment function.

COST ANALYSIS CONCEPT

The concept of cost analysis is the application of cost to the movement of water so that the total cost can be identified for the delivery of water to different points in the system. Cost centers identified within the physical system localize and trace the costs as the water moves from the source into the treatment process and through the delivery system.

Costs are first charged to cost centers within the physical system and are then transferred in increments from the cost centers to the appropriate cost zone based on the flow of revenue producing water (RPW) within the zone. A prototype of such a system has been developed for Kenton County, Kentucky. Each month, the RPW by cost zone is calculated at the Kenton Water District on a worksheet designed for this purpose. The first step in

	WATER UTILITY FUNCTION			
COST CATEGORY	ACQUISITION	TREATMENT	DELIVERY	SUPPORT SERVICES
LABOR				
POWER				
CHEMICALS				
MATERIALS				
MISCELLANEOUS				

Figure 13. Function and cost category information.

calculating the RPW is to determine the metered flow of water within each cost zone and then convert this figure to billed water by applying a conversion factor. The metered flow is determined by reading the flow meter at each booster pumping station or by applying a factor based on power consumption against the rated flow capacity of the pump station. The conversion factor of metered flow to billed water is the average RPW calculated from historical data.

Inherent in the process of transferring costs is knowledge of the physical arrangement of the utility's assets and the functions involved. Because the cost analysis report is oriented to cost zones, the location of the pumping and storage cost centers with respect to the cost zones must be known. To develop and test the cost analysis concept it was implimented in the Kenton County Water District No. 1 in Kenton County, Kentucky.

The Kenton County Water District No. 1, the first water district established in the State of Kentucky, developed its original water supply system by purchasing the Dixie Highway Water Company system in 1926. During this period of time, treated water was being purchased from the City of Covington, Kentucky and delivered by the District to its customers.

In July 1977, the Kenton Water District acquired the operating control of the City of Covington, Kentucky Water Utility. A separate cost analysis system was implemented for the Covington, since bonding restrictions required that Covington accounting be separate from that of the Kenton Water District. Therefore, reports, similar to those of the Kenton Water District, are prepared for the Covington system. Figure 14 is a map of the Kenton County Water District No. service area, showing the locations and relative sizes of the three pressure zones.

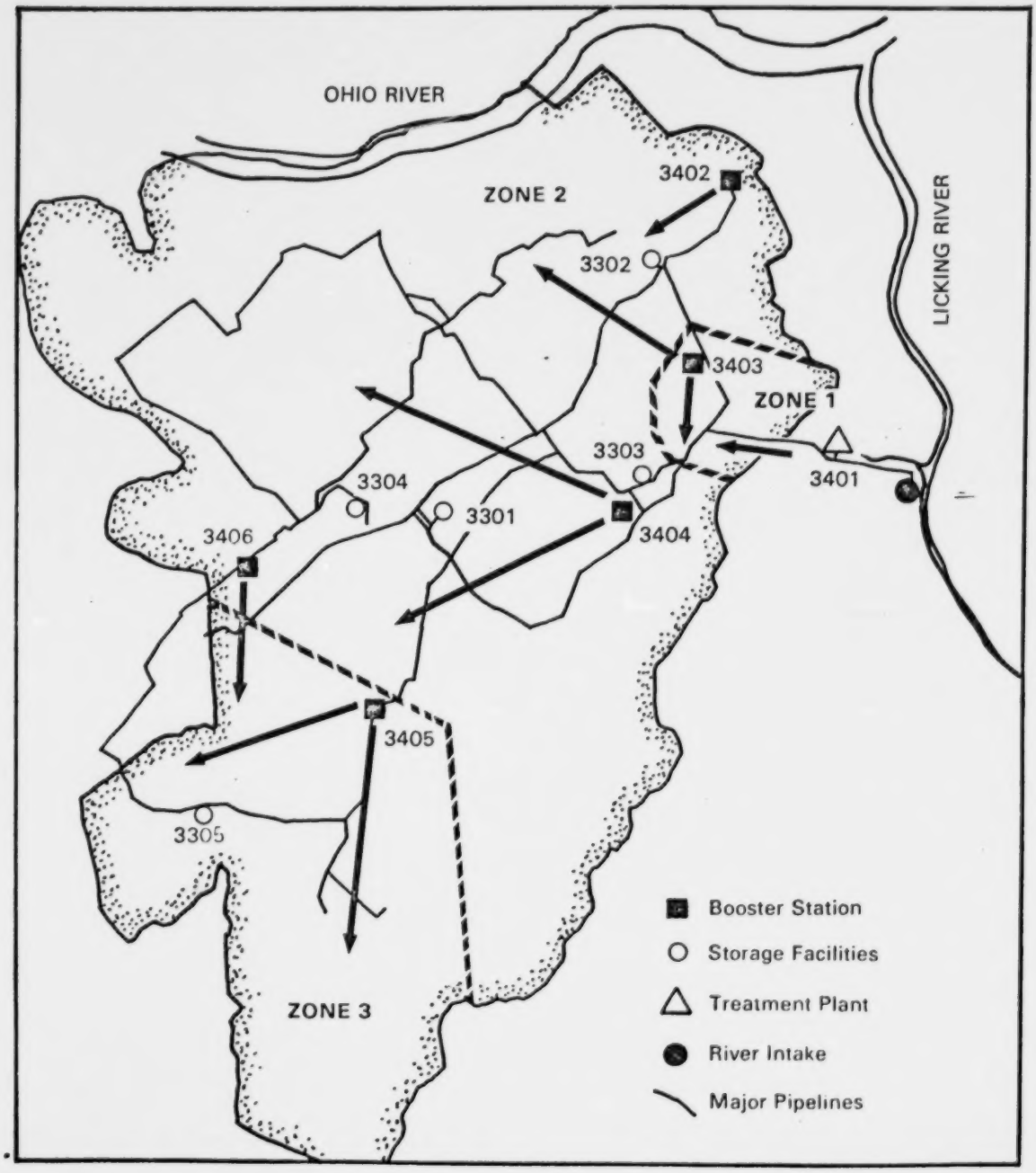


Figure 14. Kenton County Water District No. 1 service area.

CONCEPT OF OUTPUT REPORTS

As mentioned previously, the first step in the development of the cost analysis system was to identify the desired outputs. Once the outputs were established, appropriate input data were acquired, verified, and assigned to the proper cost centers. It was determined that the cost analysis system would produce two types of output: cost analysis reports and supplemental accounting reports.

Four levels of cost reports (Level 1 through Level IV) were designed to provide information for specific levels of management, ranging from detailed to summary reports.

The Level IV report was developed to provide very detailed cost information. This report assigns input cost categories to each cost enter by account description. The Level III report relates the detailed cost by broader, standardized categories. The Level II report compares actual expenditures with budgeted amounts and with expenditures for the previous year. The Level I report summarizes the cost data and identifies the $/MG of RPW for the major cost centers and the total cost for the system. Costs for the previous month, the previous year, and the budgeted amounts are also compared on the Level I report.

The cost analysis report allocates cost to the movement of water through the system from the intake to the point of consumption. It identifies costs by delivery zone, including indirect costs (by allocation). In this manner, zoned and system costs can be examined.

CONCEPT OF THE COST CLASSIFICATION SYSTEM

The cost classification system illustrated in Figure 15 provides the interface with the financial reporting system and the parallel functioning of the

cost analysis system. The first group of number (XXX-XX) designates the general ledger expense accounts. This five-digit number conforms in general to the National Association of Regulator Utility Commissioners (NARUC) Chart of Accounts.[73]

The second group of numbers (YYYY) identifies the cost centers that generate the expense. As shown in Figure 15, the first digit of the cost center number identifies the function, the second digit identifies the subfunction, and the last two digits identify the unit. The subfunction (second digit) and identification (third and fourth digits) appear only in the Level IV report.

COST ALLOCATION CONCEPT

The cost analysis system accumulates costs of water production at various cost centers located within the physical utility system. Costs are assigned to the specific cost centers as the costs are recorded and allocated when specific cost centers are not known. The cost analysis system can only fulfill its function when all cost data are charged to the appropriate cost centers. This is accomplished by identifying the correct cost center when the data are entered on the source document; i.e., payroll time card, requisition from stock form, etc. Exceptions to this procedure will occur when the cost center information is not obtained or when a general cost is involved that cannot be identified to a specific center. To deal with such exceptions, an allocation concept assigns costs to appropriate cost centers.

OPERATING EXPERIENCE

Kenton County, Kentucky, Water District No. 1 data has been processed by a cost analysis system since January 1, 1978. Overall, the performance of

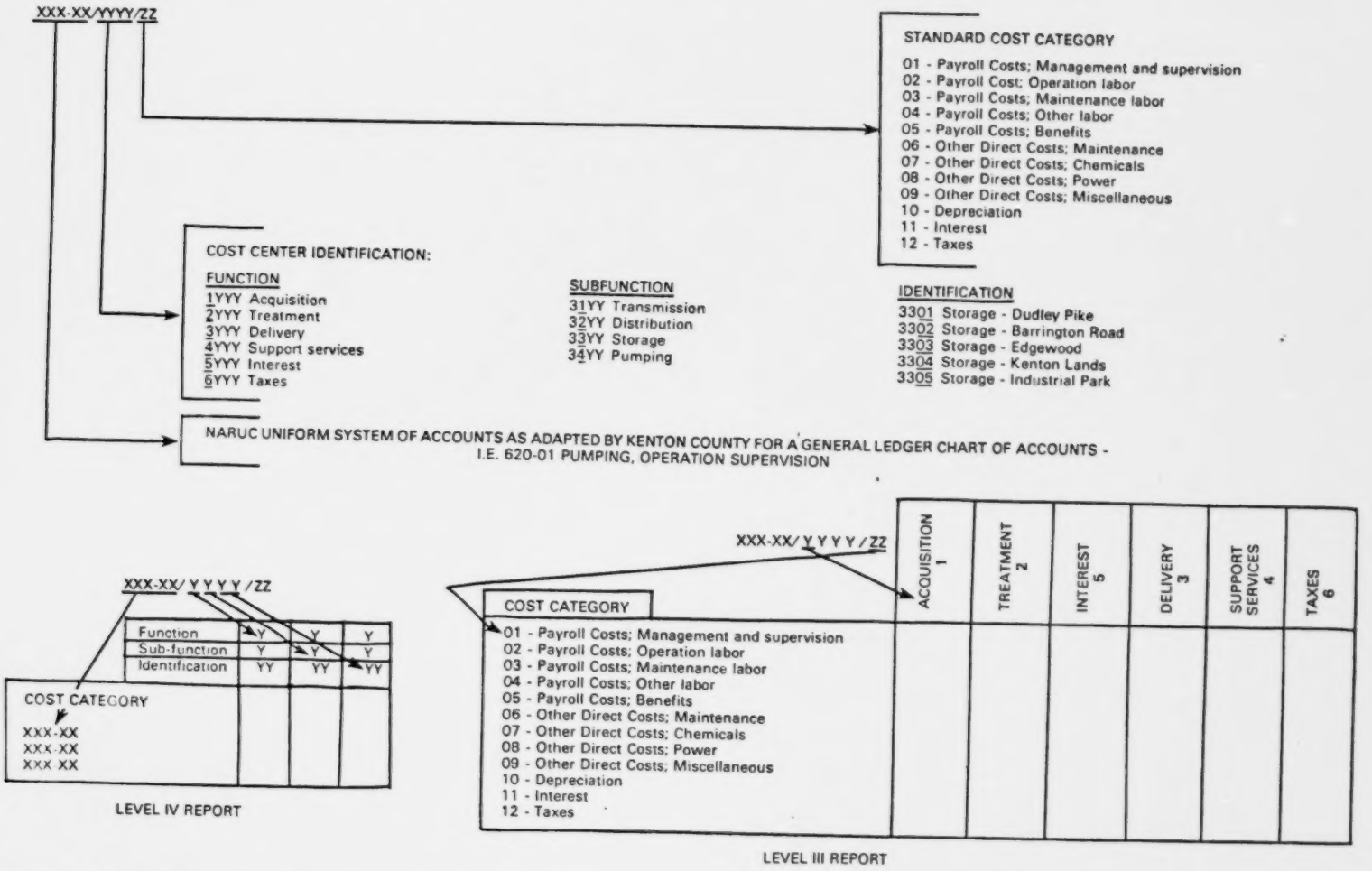


Figure 15. Cost classification system.

the cost analysis system has been impressive. In adddition to providing useful management reports, the cost analysis system has assisted in improving the existing Kenton County Water District financial reporting system.

The following three problems have been encountered with the Water District CAS system:

1. Some data entered into the manual financial reporting system were not concurrently entered into the cost analysis system. This has led to an imbalance between the two systems, and required adjustments.
2. Depreciation has been a problem within the system since Kenton County's fixed asset records were not established with the capability of identifying the proper depreciation. This necessiated the allocation of depreciated values. Depreciation is now included as a routine item in all reports.
3. The cost analysis system required input data documented to the level of cost centers. To make an account or cost center change, additional information for the computer operation must be developed. As stated earlier, this system requires that each cost be identified by a number that denotes the area where services are being performed. This is necessary in order to identify the cost to the actual cost center. Some difficulty has been encountered in having source documents coded with the proper cost centers. However, the cost analysis program will allocate those costs to cost centers even though they are not included on a source document. When this system is utilized as a mangement tool, a better understanding of its operation will be developed and the accuracy of identifying activites to cost centers will improve.

During its operation, the system has accomplished the following:

1. A cost analysis system for analyzing water supply data has been developed which does have features making it applicable to other water supply utilities. This system has been implemented and operated at Kenton County Water District No. 1
2. The system, using a matrix concept, can match operational and financial data at the top level functions of acquisition, treatment, delivery, and support services, and for two lower levels of detail.
3. This system allows a water utility manager to evaluate cost of the total utility down to the smallest component of the system. The costs are logically structured so one can move from one level to another with compatible data.
4. This system can be used to estimate the cost of water as it flows through the actual utility system and is delivered to the various consumers.
5. The reports generated by the system can be used to compare budgeted versus actual expenditures as well as a cost comparison between specific operations for different time periods, such as this year's electrical cost versus the cost of electricity for last year. After several years of information is accumulated, these features should significantly improve the capability for long-range forecasting.
6. The data base developed contains the same types of information that would be used as a base for a financial reporting system. This base, with the addition of other information such as revenues, can form a financial reporting system.
7. The system is capable of generating special, useful reports, such as payroll summaries; requisition from stock reports; payment authorization report; service contract report, etc.

After much of the development work was completed on the cost analysis system for the Kenton County Kentucky Water District No. 1, the organization acquired the responsiblity for the Covington, Kentucky Water System, and the two systems became integrated. However, because of issues relating to various bonds that were outstanding, it was decided to keep the Covington and Kenton systems separate from a cost analysis standpoint. Program adjustment were made and separate cost anlaysis reports are produced for the Covington utility. This proved that the cost analysis system could be applied to a separate utility without major reprogramming.

The cost analysis system for the two separate utilities provided the utility director with a comparison of costs. During a comparison, it was discovered that one of the treatment plants was producing water at a lower cost than the other treatment plant. Since the two systems were physically connected, the Director began to utilize the more efficient plant for the majority of the water production.

Cost analysis system reports are provided monthly allowing management, from the Commissioner level down, to review costs shortly after they have occurred. Therefore, management action can be taken when cost occur rather than later, when a major impact on the organization has taken place.

The development of a cost analysis system based on its application in Kenton County has been successful. The mangers have used it to make critical decisions regarding the utility system and have made it a routine part of their operations. They intend to use it as the basis for accounting and financial reporting in the future.

It is the authors' opinion that the system, with proper adaptation, can be applied easily to other utilities. However, additional work might have

to be done to adapt the system to a larger water utility and/or to other utility functions such as wastewater management.

SUMMARY AND CONCLUSIONS

The authors have attempted to summarize some of the large body of data, information and research which influenced the development of the Water Supply System Simulation Model. The concept of developing separate models for the acquistion-treatment and transmission-distribution portions of the water supply service network has been explored. Empirical evidence and analytical models which build on this "separate model" concept have developed. Finally a spatially oriented cost analysis system that provides operational tracking of costs in a water service network have been examined.

These concepts have provided the basis for the detailed model development discussed in Volumes I of this three volume set.

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